U.S. DEPARTMENT OF COMMERCE
National Technical Information Service
PB80-127004

Physical Chemical Treatment of a Combined Sewer Impacted Secondary Effluent

Environmental Design and Planning, Inc, Cambridge, MA

Prepared for

Municipal Environmental Research Lab, Cincinnati, OH Wastewater Research Div

Jan 80

TECHNICAL REPORT DATA

(Please read Instructions on the reverse before completing)

1. REPORT NO. EPA-600/2-80-035	2.
3. RECIPIENT'S ACCESSION NO. PB 80 127004	
4. TITLE AND SUBTITLE: PHYSICAL CHEMICAL TREATMENT OF A COMBINED SEWER IMPACTED SECONDARY EFFLUENT	5. REPORT DATE: January 1980 issuing date
	6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S): Craig B. Anderson, William C. Pisano, and Gerald L. Aronson	8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS: Environmental Design & Planning, Inc. 257 Vassar Street Cambridge, Massachusetts 02139	10. PROGRAM ELEMENT NO. 1BC822
	11. CONTRACT/GRANT NO. 11010 EHI
12. SPONSORING AGENCY NAME AND ADDRESS: Municipal Environmental Research Laboratory-Cinn. Ohio Office of Research & Development U.S. Environmental Protection Agency Cincinnati, Ohio 45268	13. TYPE OF REPORT AND PERIOD COVERED: Final Report 3/70-11/71
	14. SPONSORING AGENCY CODE: EPA/600/14

15. SUPPLEMENTARY NOTES: Project Officer: Dr. Carl A. Brunner, Chief - Systems and Engineering Evaluation Branch (513)684-7609 (FTS-684-7609)

16. ABSTRACT

A 2840 m^3/day (0.75MGD) physical-chemical wastewater treatment facility was operated at East Chicago, Indiana to demonstrate the effectiveness of chemical coagulation, filtration, and activated carbon adsorption on a combined sewer and industrial waste impacted secondary effluent. A further objective of the study was to determine the costs associated with the operation of the treatment processes.

Treatment consisted of: the addition of cationic coagulants (calcium hydroxide and ferric chloride); two stage coagulation; solids contacting and high rate sedimentation; dual media filtration; pH adjustment; and granular activated carbon adsorption. The primary coagulant (calcium hydroxide) dosage generally ranged from 185 mg/l to 415 mg/l, while the secondary coagulant (ferric chloride) was added at the rate of 17 mg/l when in use. Overall removal efficiencies of the major pollutants were as follows:

Pollutant	Average Removal Efficiency (percent)
Total Suspended Solids	81.2
BOD_5	82.0
COD	55.0
Phosphate	90.5

Primary coagulant dosage was adjusted automatically to maintain a constant electrical conductivity ratio between samples taken at the plant influent and the primary reaction zone of the solids contacting unit (Densator), generally resulting in a calcium hydroxide dosage of 330 mg/l. Since no relationship was found between the widely fluctuating influent concentration, resultant effluent characteristics and coagulant dosage, removal efficiency appeared to be insensitive to adjustments in coagulant dosage.

Performance of the carbon adsorption process was, generally, poor. Samples taken pre and post carbon treatment showed virtually no removal of BOD or phosphate, while reduction in COD averaged less than 30%. Possible explanations for these results include: 1) early and rapid exhaustion of adsorptive capacity due to carryover of shock loads through preceding treatment stages; 2) incompatibility of carbon pore structure with molecular size of waste constituents; and 3) exhaustion of carbon due to surface coating by precipitants.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Waste treatment Filtration Coagulation Adsorption Sedimentation Activated carbon treatment	Combined sewer overflows Sewage treatment plants	13B

18. DISTRIBUTION STATEMENT: RELEASE TO PUBLIC	19. SECURITY CLASS *(This Report)*: UNCLASSIFIED	21. NO. OF PAGES: 57
	20. SECURITY CLASS *(This page)*: UNCLASSIFIED	22. PRICE: A04-A01

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EPA-600/2-80-035
January 1980

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PHYSICAL CHEMICAL TREATMENT OF A COMBINED SEWER IMPACTED SECONDARY EFFLUENT

by

Craig B. Anderson
William C. Pisano
Gerald L. Aronson

Environmental Design & Planning, Inc.
Cambridge, Massachusetts 02139

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Grant No. 11010 EHI

Project Officer

Carl A. Brunner
Wastewater Research Division
Municipal Environmental Research Laboratory
Cincinnati, Ohio 45268

MUNICIPAL ENVIRONMENTAL RESEARCH LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
CINCINNATI, OHIO 45268

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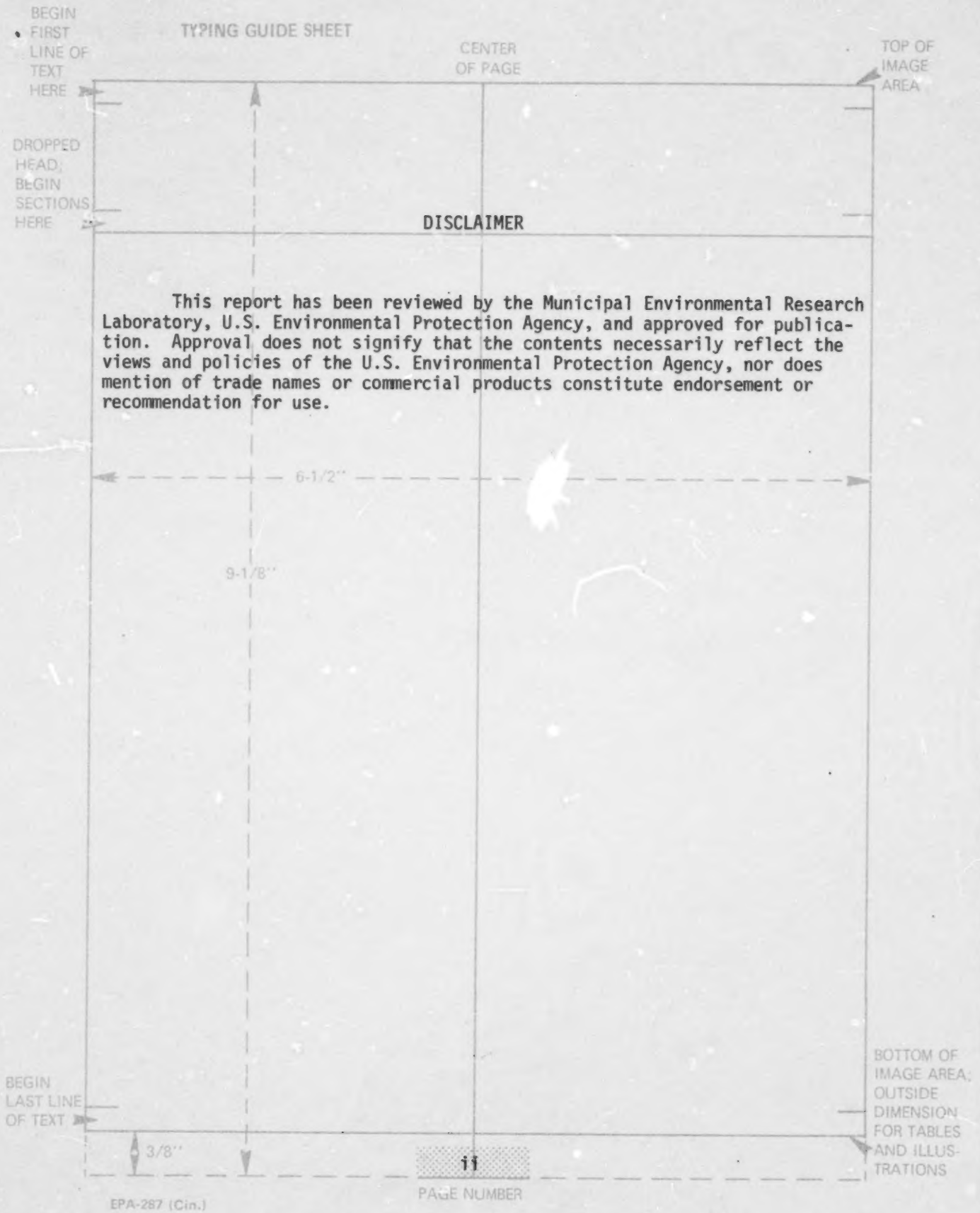
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ABSTRACT

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FOREWORD

The Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water and spoiled land are tragic testimony to the deterioration of our natural environment. The complexity of that environment and the interplay between its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solution, and it involves defining the problem, measuring its impact and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems for the hazardous water pollutant discharges from municipal and community sources, for the preservation and treatment of public drinking water supplies, and to minimize the adverse economic, social, health and aesthetic effects of pollution. This publication is one of the products of that research; a most vital communications link between the researcher and the user community.

Physical-chemical treatment of conventional biological secondary effluent for the removal of organic and inorganic pollutants is used and considered applicable in areas where secondary treatment alone is incapable of producing satisfactory effluent quality. This report describes the results of a pilot scale study performed at East Chicago, Indiana, in which an evaluation was made of the effectiveness of treating biological secondary effluent impacted by combined sewer and industrial wastes with lime coagulation, dual media filtration and activated carbon adsorption.

Francis T. Mayo
Director
Municipal Environmental Research
Laboratory

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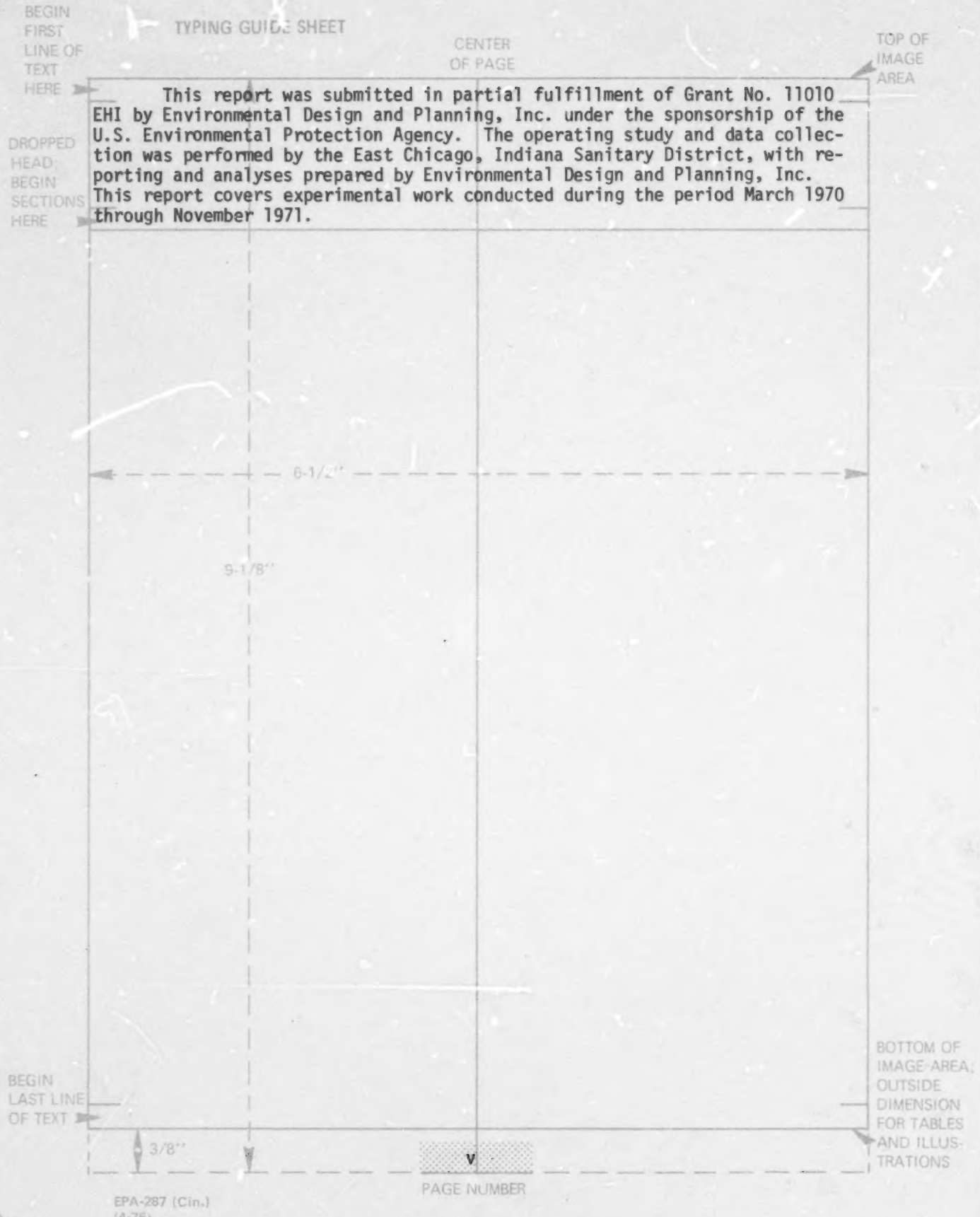
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This report was submitted in partial fulfillment of Grant No. 11010 EHI by Environmental Design and Planning, Inc. under the sponsorship of the U.S. Environmental Protection Agency. The operating study and data collection was performed by the East Chicago, Indiana Sanitary District, with reporting and analyses prepared by Environmental Design and Planning, Inc. This report covers experimental work conducted during the period March 1970 through November 1971.
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LIST OF ABBREVIATIONS AND SYMBOLS

Abbreviations

cm	-- centimeters
ft	-- feet
gpd/ft^2	-- gallons per day per square foot
gpm	-- gallons per minute
gpm/ft^2	-- gallons per minute per square foot
hr	-- hour
in	-- inch(es)
JTU	-- Jackson Turbidity Units
kwh	-- kilowatt hours
kg	-- kilogram
l	-- liter
lb	-- pound
log	-- logarithm
m	-- meter
m/hr	-- meter(s) per hour
mg	-- milligram
mm	-- millimeter
MGD	-- million gallons per day
r^2	-- portion of the total variation about the mean (predicted by the regression equation) which is explained by the regression

Symbols

BOD, BOD_5	-- Biochemical Oxygen Demand (5 day)
Ca^{++}	-- Calcium ion
$CaCO_3$	-- Calcium Carbonate
COD	-- Chemical Oxygen Demand
Mg^{++}	-- Magnesium ion
N	-- Nitrogen
pH	-- negative log of molar hydrogen ion concentration
PO_4	-- Phosphate
σ	-- standard deviation

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ACKNOWLEDGMENT

Special thanks are given to Timothy W. Raykovich, M.D., Acting General Superintendent, and Daniel R. Olson, Chief Chemist, both of the East Chicago Sanitary District, for their assistance in the preparation and interpretation of the data reported. Dr. Raykovich supervised most of the pilot plant operations, while Mr. Olson carried out the laboratory analyses.

Further thanks are given to Dr. Carl A. Brunner, Project Officer, and Richard P. Traver, Storm and Combined Sewer Section, U.S. Environmental Protection Agency, for their cooperation and assistance.

This report was prepared under the supervision of William C. Pisano, Ph.D., and Gerald L. Aronson, and written by Craig B. Anderson, all of Environmental Design and Planning, Inc.

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CHAPTER 1

INTRODUCTION

In recent years much attention has been given to the degradation of the nation's surface waters resulting from the discharge of municipal and industrial wastes. Increased population densities coupled with the demand for improvement in water quality of receiving streams has virtually necessitated the implementation of secondary treatment of municipal wastewaters. In some areas, however, the application of biological secondary wastewater treatment has been found inadequate to prevent the discharge of many undesirable, hazardous and toxic substances. These substances include: 1) inorganic/organic nutrients, such as nitrogen and phosphorous compounds, which promote algal growth; 2) organic materials which contribute to biochemical oxygen demand, chemical oxygen demand, taste, color and odor; 3) bacterial and enteric viruses; 4) colloidal solids; and 5) soluble minerals and heavy metals.

Recognizing the need for current operational experience in the use of physical-chemical treatment methods, the U.S. Environmental Protection Agency initiated a number of demonstration scale investigations to provide information on treatment performance and operating costs. The results of the study given in this report reflect the experience gained during the operation of a 2840 m^3/day (0.75MGD) physical chemical treatment plant at East Chicago, Indiana, demonstrating the effectiveness of chemical coagulation, solids contact, filtration and activated carbon adsorption on a combined sewer and industrial waste impacted secondary effluent.

Operation of the pilot plant began in November 1969 following a one-year construction period, with the implementation of the solids contact and filtration processes. As the plant was put on stream, a variety of construction related and mechanical equipment problems were discovered, the initial shakedown period continuing into the spring of 1970, with many of the construction related difficulties rectified by the end of May. Carbon treatment was postponed until summer of 1970 to avoid overlapping and compounding operational difficulties found in the upstream processes. The pilot studies continued through October 1971. The period of October and November 1970 appeared to give characteristic performance results and were, therefore, selected for review in the analysis contained in this report.

Following the introductory comments given in this section, Chapters 2 and 3 furnish conclusions and recommendations resulting from the pilot study. Chapter 4 provides a historical background of physical-chemical treatment and includes fundamentals of process theory. A description of the

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pilot plant and its characteristics is provided in Chapter 5, while Chapter 6 gives influent characteristics, discusses overall removal and relates removal performance to the operation of the unit processes. Chapter 7 presents a summary of cost data generated as part of this study.

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CHAPTER 2

CONCLUSIONS

- Physical-chemical treatment of a stormwater and industrial waste-impacted municipal secondary effluent has been shown to be an effective method of substantially reducing BOD, COD, phosphates and suspended solids carried over from secondary treatment.

- Effluent quality is good to excellent. Overall removal efficiencies of major pollutants are given below:

Pollutant	Average Removal Efficiency (percent)
Total Suspended Solids	81.2
BOD_5	82.0
COD	55.0
Phosphate	90.5

- For the more significant pollutants, high correlations were exhibited between removal performance and applied pollutant concentration.

- Since no relationship was found between widely varying influent pollutant concentration, resultant effluent characteristics and coagulant dosage, removal efficiency appeared insensitive to adjustments in coagulant dosage.

- The most significant pollutant removal occurred in the solids contact and filtration processes. Activated carbon treatment results were unexpectedly poor, with less than 30 percent COD removal. It is felt that poor carbon removal was due to surficial coating, acting to reduce effective carbon surface area.

- Conductivity control of lime dosage produced erratic feeding of coagulant due to fouling of the conductivity cells. Frequent maintenance of these cells was required to obtain satisfactory feed results. Additional difficulty was encountered in maintaining proper lime dosage due to buildup of lime in the slurry solution lines and lime feed apparatus.

- The solids contact process proved difficult to control, resulting from the variability in the coagulation process. Sludge blanket levels varied significantly, often producing carryover of calcium carbonate floc to filtration.

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CHAPTER 3

RECOMMENDATIONS

The purpose of this chapter is to summarize significant process deficiencies and operating problems encountered during this study, and to point out some of the remedial actions necessary to minimize or eliminate such deficiencies.

The following are key points of recommendation:

- The results of this study showed difficulty in maintaining stable solids contact process operation, leading to fluctuating treatment performance. It is recommended that solids contact only be applied after careful consideration of the variability in influent waste strength and flow characteristics.

- Considerable difficulty was encountered in the use of conductivity measurement for control of coagulant dosage. Since the primary purpose of conductivity control is in coagulant adjustment for optimum completion of softening reactions, its applicability should be evaluated in light of interferences presented by influent characteristics. If conductivity control is selected, adequate cleaning and maintenance should be provided in an attempt to prevent erratic measurement resulting from cell scale buildup and fouling evidenced in this study.

- Recurrent difficulty existed in the feeding and conveyance of lime to the densator mixing chamber, the most significant of which was the deposition of lime and calcium carbonate scale on slurry solution lines. In an effort to minimize solution feed problems, it is recommended that presoftening of solution water be considered in an attempt to reduce precipitation of calcium carbonate hardness on solution feed lines, and that periodic manual or automatic flushing of solution lines be performed.

- Application of full-scale carbon adsorption should be preceded by jar studies and pilot testing using several grades of carbon in an effort to provide an evaluation of anticipated treatment performance. If pretreatment is considered in plant scale design, its effect upon carbon performance should be accounted for in pilot testing programs.

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CHAPTER 4

PHYSICAL-CHEMICAL TREATMENT - A BACKGROUND

4.1 Introduction

Physical-chemical treatment is an old concept dating back many centuries, first seen in the treatment of potable water. Sanskrit medical lore and Egyptian inscriptions indicate that in addition to heating, boiling or filtration, a variety of mineral and vegetable substances, principally the seed of *Strychnos potatorum*, were used to purify water. Alum (argilla of Italy) and Lime (chalk of Rhodes) were first described by Pliny (ca. 77 A.D.) as effective additives, rendering bitter water potable.

In modern times, chemical coagulation was revived during the 1600's by Sir Francis Bacon and others. Alum was used in England during the late 1700's to render muddy water fit for consumption. Large-scale use of coagulation first became popular in British industrial plants in the early nineteenth century and was first instituted for treatment of the municipal water supply in Bolton, England[1].

As experience was gained in chemical coagulation of water supplies, development of its application to municipal wastewater treatment was also taking place. Chemical precipitation of wastewater was well established in England as early as 1870. In most cases lime was the sole coagulant, but was frequently used in conjunction with calcium chloride, magnesium chloride, alum, ferrous sulphate, charcoal or a number of other substances[2].

Carbon purification of gases and liquid solutions originated in the eighteenth century when the phenomena of adsorption was discovered. Scheele first described the adsorption phenomena in his use of carbon in experiments with gases in 1773; while Lowitz observed in 1785 the ability of carbon to decolorize many liquids. Industrial application of adsorption occurred several years later when wood char was applied in refining cane sugar[3]. In the nineteenth century, charcoal treatment was extended to the adsorption of tastes and odors from several municipal water supplies in England. The "activation" process in which the adsorptive powers of charcoal are enhanced is a relatively recent development, taking place in the early years of this century.

Extensive use has been made of the purification properties of activated carbon since its development. Widespread use of activated carbon gas masks was made during both World Wars I and II. The food, pharmaceutical, petroleum, chemical and water processing industries have since advanced the

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science of activated carbon purification and have adopted carbon treatment as a common practice.

Physical-chemical treatment of wastewater was fairly extensive in the United States in the 1890's and early 1900's, but its use was largely eclipsed by the development of biological treatment processes in the first part of this century. Renewed interest in physical-chemical treatment in recent years stems from the demand for effluents superior in quality than those obtainable from biological treatment, and from limitations imposed on the effectiveness of biological treatment where toxic substances are present or where treatment is subject to wide variations in influent waste characteristics.

4.2 Treatment by Chemical Clarification

The application of chemical clarification in wastewater treatment has as its objectives the removal of suspended or dissolved contaminants through precipitation reactions combining pollutants and the chemical additives into insoluble species, and destabilization and collection of impurities through interparticle attractions formed by the additives. The nature of the reactions involved in the precipitation of wastes is extremely complex due to the non-homogeneous nature of the wastes, and due to multiple and often interfering reactions which may occur. Rarely do precipitation reactions proceed to completion as predicted by stochiometric relationships.

Lime reacts with both natural carbonate hardness and carbonate and bicarbonate alkalinity to form insoluble calcium carbonate, the primary precipitant used in removing finely dispersed settleable colloids and hydrophobic colloids. The presence of excess calcium ions in water acts to destabilize colloidal suspensions and promote formation of complex molecules which, with the aid of the heavy calcium carbonate particles, are readily settled. When magnesium is present in significant amounts, excess lime treatment also permits formation of the gelatenous precipitant magnesium hydroxide, which is an aid in the removal of colloids. The combined effect is the destabilization of suspended materials and their physical agglomeration, resulting in a suspension which can then be removed by sedimentation.

Significant removals of phosphate compounds can be accomplished through lime treatment. Once the bicarbonate alkalinity has been satisfied by the addition of lime, excess calcium ions are available for the formation of the precipitate hydroxyapatite, containing phosphate. Removal of the phosphates is then promoted by flocculation with other precipitants, followed by sedimentation.

Ferric chloride, when added to water, undergoes a series of hydrolytic reactions, generating polynuclear hydroxyl complexes which act to destabilize colloidal particles contained in the waste. The end result of ferric chloride addition is the creation of insoluble ferric hydroxide which, upon flocculation, forms the nucleus for capturing destabilized colloids.

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4.3 Solids Contact Process

Solids contact is a process employing chemical and physical reactions in the presence of previously precipitated solids supplied by sludge recirculation to the treatment unit influent. Its use is often applied in the removal of hardness from water supplies through calcium carbonate and magnesium hydroxide precipitation. The objectives of the process are to increase agglomeration reactions and promote floc growth, and to enhance sedimentation through sludge blanket development.

It has been found in water treatment that the amount of calcium and magnesium precipitation increases significantly when lime-treated hard water is brought into contact with previously precipitated calcium carbonate (4). This type of treatment has the effect of speeding the calcium carbonate formation reactions by providing sites for the development of the newly formed calcium carbonate. Further, it has been found that when previously precipitated solids are recirculated in concentrations of 5 percent by weight or greater, an improvement in precipitation of magnesium can be expected (4).

Solids contact units have proven to be an efficient method for chemical treatment where influent characteristics and flow rate remain relatively constant. Difficulties in maintaining solids contact process performance have been encountered where influent conditions are subject to variation. It is for this reason that GLUMRB Standards(5) for water supply state that this is acceptable when "water characteristics are not variable and flow rates are uniform". Under other conditions, the Standards stipulate that use of the process is acceptable only with approval of reviewing authorities.

Problems encountered in use of this process are the inability to maintain stable sludge blankets and the development of septic clarifier conditions(6). The principal advantage of the process is the significant size reduction of the clarifier, resulting from higher loading rates allowed by solids contact.

4.4 Filtration

Filtration of chemically treated wastewater removes particles remaining in the waste stream following the flocculation and sedimentation steps which precede it. Removal of material is accomplished by a series of complex phenomena, including adsorption, flocculation, sedimentation and straining.

In dual media filters significant flocculation and sedimentation of solids may occur in the upper layer of coarse anthracite, while surface contact promotes adsorption in both the upper and lower layers. Solids removal is largely influenced by the grain size of the filter media and by the size, shearing characteristics and adhesive characteristics of the floc. Sizing of filter media is critical to the success of the filtration process and is a compromise between selection of finely graded material necessary to prevent early breakthrough of small floc particles, and selection of coarse media necessary to permit adequate floc storage without excessive hydraulic losses or prematurely-short filter runs.

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Dual media filtration has gained wide acceptance in recent years, since it provides two distinct advantages over conventional single media rapid filters. These are (1) increased effective filter bed depth, prolonging length of filter runs, and (2) the ability to withstand increased hydraulic application rates without encountering excessive head losses. The dual media filter typically consists of a coarse coal layer about 46 cm (18 in) deep above a fine sand layer about 20 cm (8 in) thick, resting on a porous underdrain collection system (4). Conventional single media filters are graded fine to coarse due to grain size segregation occurring during the backwash process. In the dual media filter the coarser anthracite particles settle on top of the sand after backwashing, due to the lower settling velocity of the lightweight material. The coarse upper layer of coal contains large pore spaces in which the applied floc is entrapped. The underlying finely graded sand layer contains much smaller pores, acting to collect fine particles at its surface.

4.5 Activated Carbon Adsorption

Activated carbon removes contaminants from wastewater by adsorption, the attraction of one substance on the surface of another. The principal characteristic giving activated carbon its great adsorptive capacity is the high surface area and minute pore structure created in the carbon activation process, with surface areas reaching typical values of from 500 to 1400 square meters per gram[3]. Activated carbon is a selective material having an affinity for organics, which makes it highly suitable for treating of wastes which have only a high organic content, or for inclusion in a treatment scheme in which solids and inorganics are selectively removed by other methods.

Two standard approaches exist for the application of activated carbon to wastewater treatment. The first approach is to apply carbon treatment in a "tertiary" treatment scheme following conventional primary and biological secondary treatment. Such treatment may include carbon adsorption only, or additional chemical clarification and filtration followed by carbon adsorption. An alternative arrangement is to provide physical-chemical treatment only and eliminate biological treatment altogether. This method of treatment is selected where biological treatment is infeasible due to the nature of the wastes, or where performance attained by physical-chemical treatment makes the use of preceding biological treatment economically impractical.

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CHAPTER 5

PROCESS DESCRIPTION

5.1 Design Considerations

The East Chicago advanced waste treatment pilot plant incorporated the following unit treatment operations: chemical precipitation/solids contact, dual media filtration and activated carbon adsorption. Lime precipitation was selected as the primary chemical treatment mechanism, taking advantage of natural hardness and alkalinity in the wastewater to affect the desired calcium carbonate precipitation reactions.

Hydraulic capacity of the plant was set at 2840 m^3/day (0.75 MGD), to be supplied at essentially constant rates, with the capability of operating at rates from 1136 to 2840 m^3/day (0.3 to 0.75 MGD). The plant was operated at design capacity throughout the study. Plant specifications giving characteristic influent criteria are shown in Table 1, with desired effluent goals shown in Table 2. The treatment scheme, including solids contact, filtration and activated carbon adsorption, is shown in Figure 1.

5.2 Solids Contact Process

The first stage of treatment included the use of a proprietary solids contact unit (Infilco DENSATOR) in which coagulant was introduced, followed by rapid mixing, flocculation, solids contact and sedimentation. The Densator, consisting of a 6.71 m (22 ft) diameter by 5.18 m (17 ft) high steel shell, provided a settling area of 27.64 m^2 (297.6 ft^2), giving a nominal settling rate of 102.75 m/day (2517 gpd/ft^2) at the design flow of 2840 m^3/day (0.75 MGD). Details of the physical arrangement of the Densator are shown in Figures 2 and 3.

The following describes the function of the operating zones of the unit:

Zone 1 - Primary Reaction Zone

Dense recirculated solids, raw water and lime were intimately mixed in the primary reaction zone. Application of lime was controlled by a conductivity cell which proportioned the lime feed to maintain a constant conductivity ratio between the raw water and water contained in the primary reaction zone.

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TABLE 1: INFLUENT DESIGN CRITERIA

Suspended Solids	0 to 50 mg/l
Turbidity	10 to 50 JTU
Total Dissolved Solids	500 to 1000 mg/l
pH	7.0 to 8.0
Total Alkalinity	175 to 275 mg/l as $CaCO_3$
Color	10 to 120 alpha color units
Hardness	300 to 600 mg/l as $CaCO_3$
Chloride	150 to 300 mg/l
Sulfate	250 to 600 mg/l
Ammonia Nitrogen	5 to 50 mg/l as N
Total Phosphate	1 to 5 mg/l as PO_4
Biochemical Oxygen Demand	20 to 50 mg/l
Chemical Oxygen Demand	30 to 100 mg/l
Dissolved Oxygen	0 to 5 mg/l
Phenol-like Substances	0 to 100 micrograms/l
Methylene Blue Active Substances	0 to 2 mg/l

TABLE 2: EFFLUENT QUALITY GOALS

Suspended Solids	1 mg/l
Turbidity	1 JTU
pH	6.5 to 9
Color	25 color units
Total Phosphate	1 mg/l
Biochemical Oxygen Demand	10 mg/l
Chemical Oxygen Demand	15 mg/l
Dissolved Oxygen	3 mg/l
Phenol-like Substances	20 micrograms/l
Methylene Blue Active Substances	0.5 mg/l

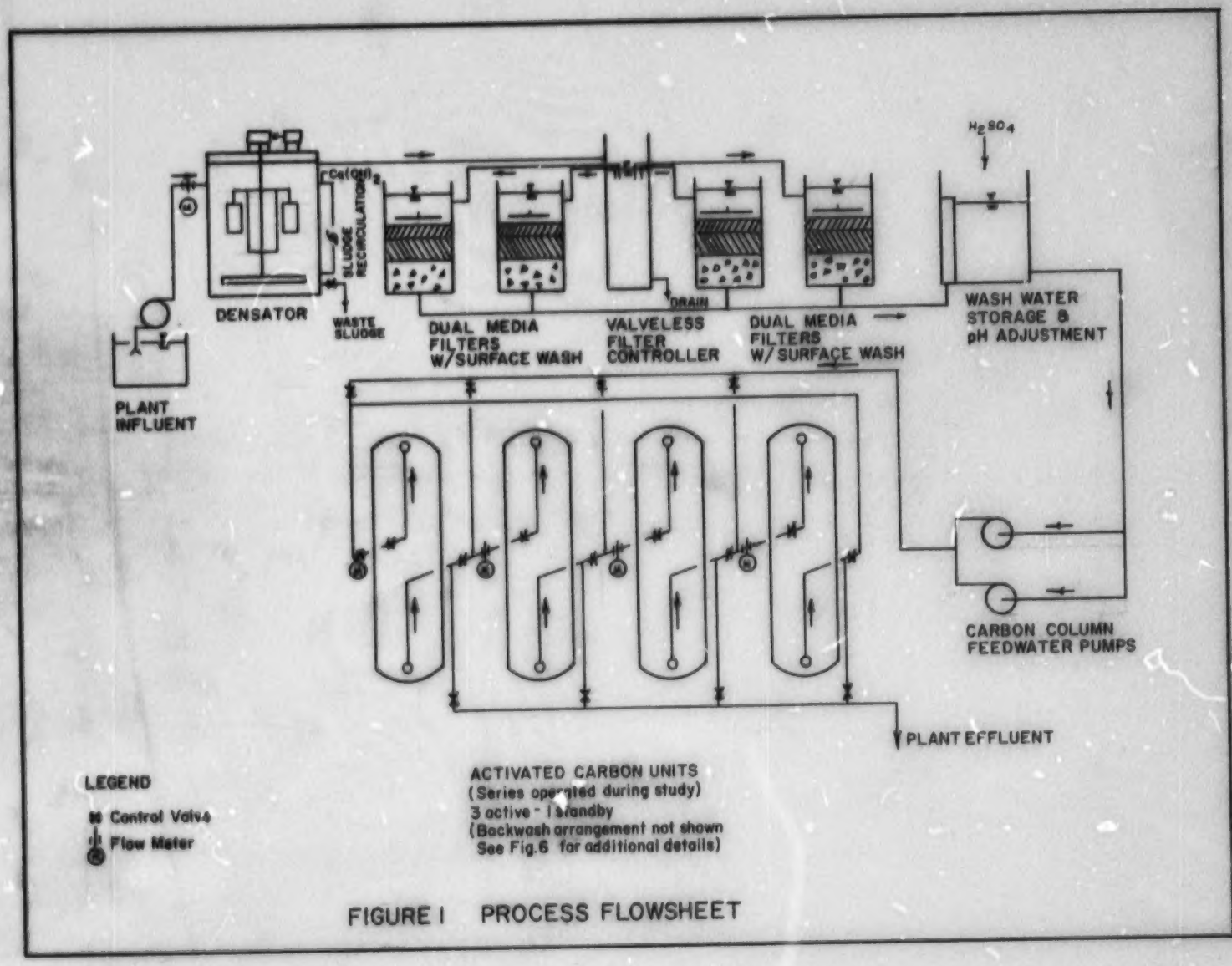

FIGURE 1 PROCESS FLOWSHEET

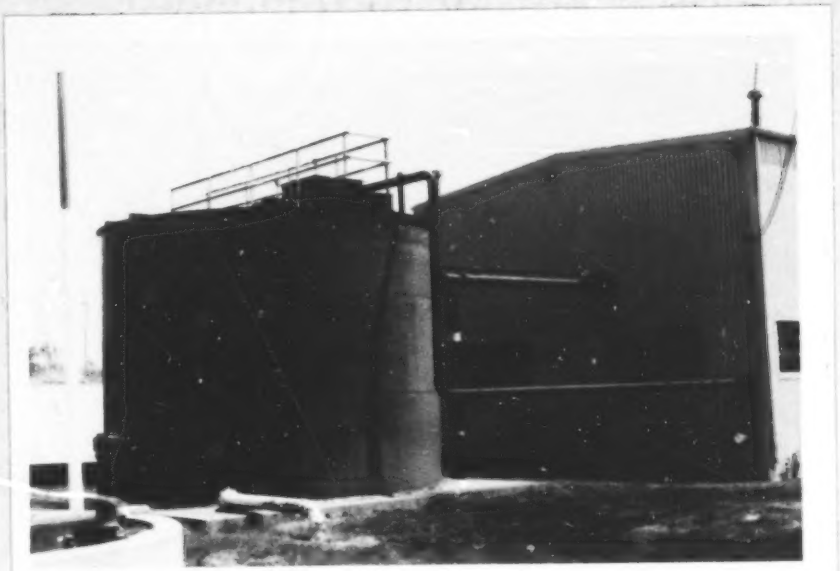

FIGURE 2. 0.75 MGD DENSATOR UNIT

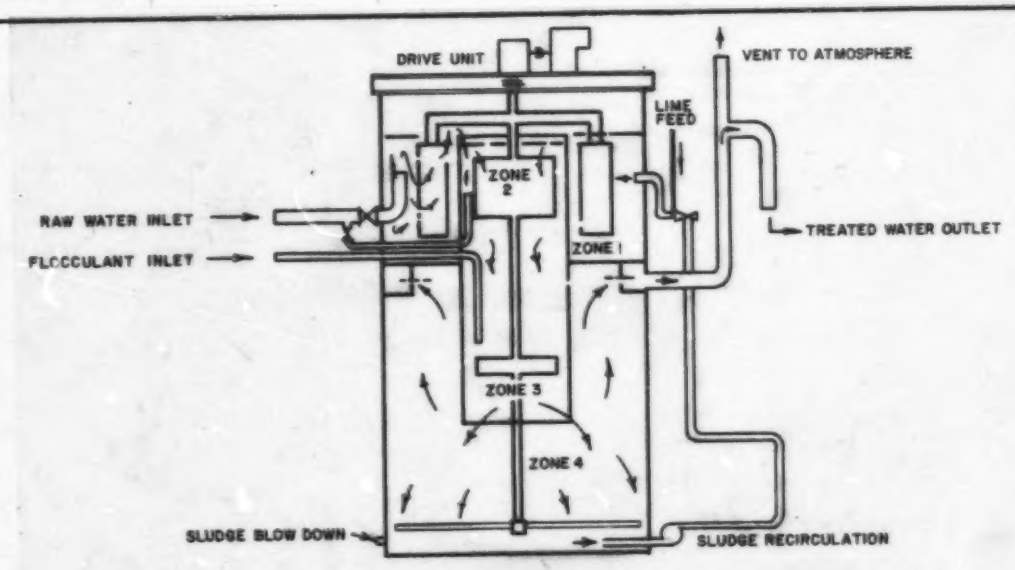

FIGURE 3 DENSATOR DETAILS

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Zone 2 - Secondary Reaction Zone

A portion of the influent stream was diverted and introduced directly into the secondary reaction zone. Excess lime applied in the primary zone was used to complete the coagulation and precipitation reactions in this zone.

Zone 3 - Coagulation and Flocculation Zone

Ferric chloride coagulant, when in use, was introduced into this zone to improve the lime coagulation process.

Zone 4 - Sludge Separation Zone

Solids were separated from the liquid in this zone. Settling of lime floc took place to form a sludge blanket, entrapping newly introduced solids. Level adjustment of the sludge blanket was made by controlled wasting of sludge and by varying the rate of sludge recirculation. Supernatant was withdrawn from the upper level of this zone through a series of peripheral submerged orifices. Determination of sludge blanket levels was made by taking sludge samples from a vertical row of sample taps located on the sidewall of the unit. Sludge recirculation was maintained to produce a solids concentration in the primary reaction zone of approximately 3% by weight.

The Densator was furnished with two independent drive systems, one providing power to the mixing blades in primary, secondary and flocculation zones, the other providing power to sludge scrapers located at the bottom of the sludge separation zone. The mixing blades were sized to produce a gradually decreased rate of mixing as the flow passed through the unit.

5.3 Filtration

Following the coagulation and sedimentation phases of treatment, filtration was employed to remove carryover of unsettled floc. Filtration was accomplished through the use of four dual media filters, each comprised of a two-layer bed of 1.0 mm diameter anthracite coal overlaying 0.5 mm silica sand. Details of filter beds are given in Table 3.

TABLE 3 : FILTER CHARACTERISTICS

Number of Units	4
Type of Operation	downflow, gravity
Operating Configuration	parallel
Bed Size	2.59m (8.5ft) dia
Media Type	1.0 mm anthracite 0.5 mm sand
Application rate	5.39 m/hr (2.20 gpm/ft^2)

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Influent to the filters was furnished at a constant rate by a valveless filter controller. The filter effluent was delivered to an unvalved common mainfold system supplying the neutralization and backwash storage tank (see Figure 1). Supply to the neutralization tank was delivered over an inlet weir set at an elevation higher than the filter media to prevent negative head conditions from occurring during filtration, and to create a constant head differential over the washwater launders during backwashing.

During filtration increased head loss results in a rise in height of the water surface over the filter bed. Backwash was initiated automatically when filter controls detected excessive loss of head conditions through the filter media. Influent to each filter was supplied by an individual siphon contained in the filter controller. At the end of a filter run, the supply siphon was broken, removing the filter from service, and a washwater siphon was created, educting washwater from effluent launders located above the filter bed. Gravity flow of washwater was obtained from the effluent of the filters remaining in service. Supplemental washwater was furnished by pumping from water stored in the neutralization reservoir.

The filters were supplied with surface washwater arms whose high pressure nozzles enhanced scouring of the anthracite layer. Surface washing developed the increased turbulence necessary to cleanse the lightweight material, thus reducing the overall backwash water requirements.

5.4 Activated Carbon Adsorption

Supply to the activated carbon columns was taken from the washwater and neutralization storage reservoir. The pH directly following filtration typically ranged from 8.5 to 10.5. At elevated pH values, carbon adsorption is often inhibited with desorption occurring as carbon capacity nears exhaustion. Sulphuric acid was applied to the carbon column feedwater at the neutralization tank to prevent this possibility.

Four downflow pressurized carbon beds were incorporated into the design scheme at East Chicago. The columns were arranged to permit either series or parallel operation with three units in service and a fourth held in reserve. Series operation was selected for use throughout the study period. The operation of carbon columns was sequentially rotated on a periodic basis, permitting backwashing of the unit removed from service. Head losses were monitored for each of the columns as a check against alteration of backwash frequency. Table 4 gives typical carbon column characteristics, and a view of the carbon columns is shown in Figure 4. Details of the valving to each carbon contactor are shown in Figures 5 and 6.

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TABLE 4 : CARBON COLUMN CHARACTERISTICS

Number of Units (total)	4
(in service)	3
Type of Operation	downflow, pressure
Operating Configuration	series
Bed Size (each)	3.66m (12 ft) dia x 3.35m (11 ft) deep
Media Type	Granular Darco 8x35
Empty Bed Contact Time (each)	18 minutes
(total)	54 minutes
Application rate	10.8 m/hr (4.5 gpm/ft^2)

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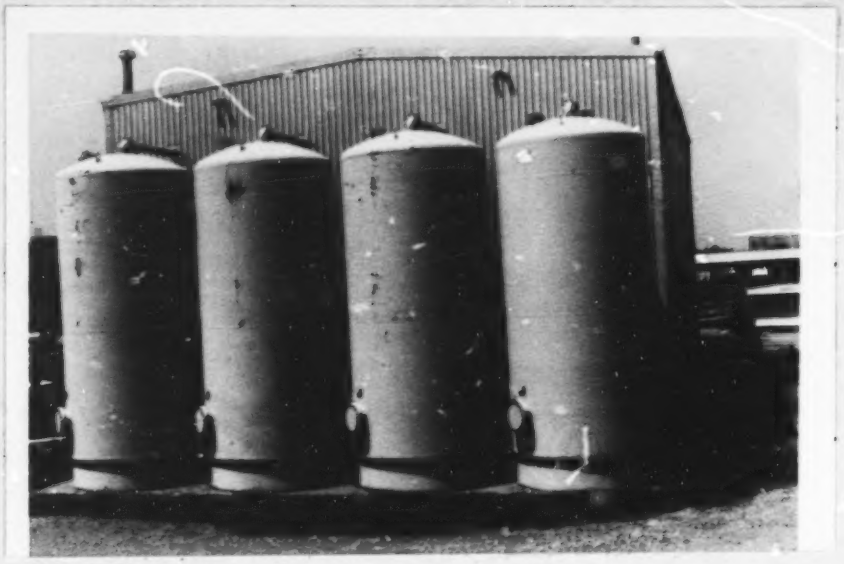

FIGURE 4. ACTIVATED CARBON ADSORPTION COLUMNS

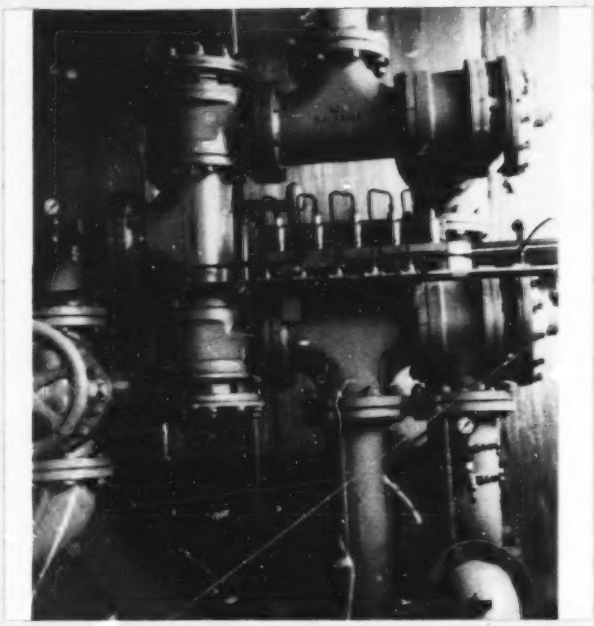

FIGURE 5. CARBON COLUMN CONTROL VALVE ASSEMBLY

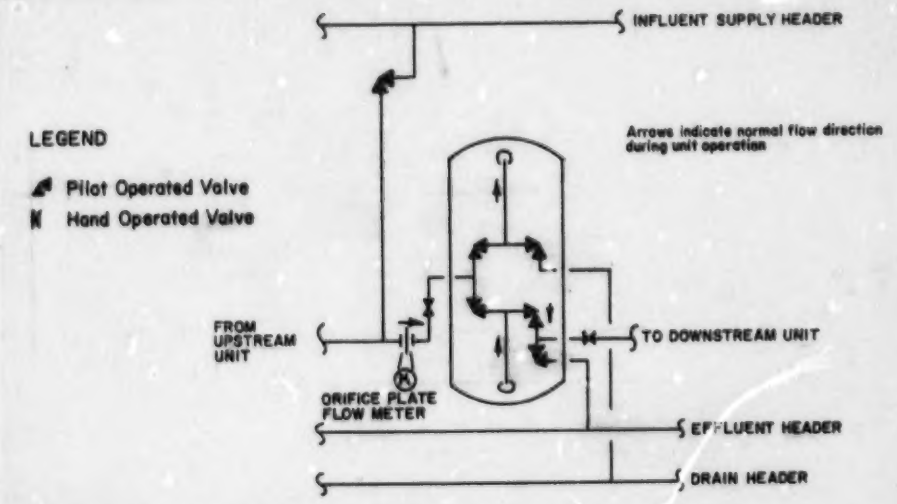

FIGURE 6 CARBON COLUMN CONTROL VALVE DETAILS

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CHAPTER 6

TREATMENT PERFORMANCE

6.1 Pilot Plant Operations

Subsequent to a one-year construction period, operation of the pilot plant began in November 1969 with the implementation of the solids contact and filtration processes. As the plant was put on stream, a variety of construction-related and mechanical equipment problems were discovered, limiting the duration of Densator and filter runs. The initial shakedown period continued into the spring of 1970, with many of the construction-related difficulties rectified by the end of May. Carbon treatment was postponed until summer of 1970 to avoid overlapping and compounding operational difficulties found in the upstream processes.

The most significant ongoing equipment breakdowns were related to the control and feeding of lime. Conductivity sensors exhibited fouling and scale formation, preventing a true and accurate comparison of conductance between the influent and reaction zones of the densator. This condition was closely monitored, necessitating frequent cleaning of the conductivity cells. Additionally, excessive deposition of lime and calcium carbonate was evidenced in lime slurry solution lines, requiring flushing of the slurry feed lines with hot water. The volumetric lime feeder also required frequent attention to prevent the discharge ports from becoming clogged with caked lime.

While equipment problems were being resolved, the Densator was evaluated to determine the most effective mode of operation. Significant floc carryover was reported in early periods of the study, and continual adjustments in sludge wasting schedules were made in an attempt to lower sludge blanket levels to prevent this condition. The problem of floc carryover persisted sporadically throughout most of the study period, resulting primarily from the variability in: 1) lime reactions with the influent; 2) the method of lime feed control; and 3) the fixed time proportionate nature of the sludge wasting control.

Carbon treatment was initiated on an intermittant basis in early July 1970, with continuous operation beginning on July 18. Since it was expected that contaminant concentrations entering and leaving the columns would be low, influent and effluent of the columns were collected by automatic refrigerated compositing samplers, reducing error introduction resulting from sample instability. After initial backwashing, the columns operated for approximately two weeks without further cleaning. Shortly following this, a

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plant upset forced curtailment of carbon treatment until the upstream treatment train had stabilized. After treatment was resumed, carbon column head loss became excessive, requiring a backwash interval of six days. This condition gradually abated so that by the fall of 1970, backwash frequency was from one to three weeks.

The pilot plant continued operating for most of the remainder of 1970, with solids contact, filtration and carbon adsorption treatment. Toward the end of December, excessive lime deposition developed in the slurry feed pipelines, forcing a plant shutdown. A series of piping failures followed which resulted from freezing conditions, forcing the plant to remain inactive through January 1971 while repairs were made. An upset in biological secondary treatment caused severe foaming in the Densator influent in February shortly after the plant was placed back in service, causing erratic lime feeding through false conductivity measurements. This upset forced an attendant shutdown in the pilot plant resulting in leaks due to frozen piping.

Lime deposition was again evidenced in slurry solution lines shortly after the plant was placed in service at the beginning of March. This continuing problem forced plant shutdown while slurry pipelines were cleaned with a dilute acid solution, the plant being placed back in service at the beginning of April.

Pilot studies continued through October of 1971 with performance similar to that described previously, e.g. the most significant and recurrent difficulties remained in the feeding of lime and the maintenance of stable Densator operation. The period of October and November 1970 appeared to give characteristic performance results and were, therefore, selected for review in the analysis contained in the following sections.

6.2 Influent Characteristics

Influent to the physical chemical treatment plant was taken from the biological secondary effluent of the East Chicago municipal wastewater treatment plant, and includes a combination of sanitary and industrial wastes which are subject to the influence of stormwater runoff. Due to the variety of waste constituents, and to waste strength fluctuations resulting from storm events, the performance of secondary treatment fluctuates widely, creating a pilot plant influent of varying quality. Figures 7 through 12 show average weekly plant influent and effluent concentrations for the representative period of October and November 1970. It is especially interesting to note that COD and phosphate levels show the greatest amount of variability, with minimum and maximum daily fluctuations as wide as 5 to 1. Influent BOD appears more stable than COD, the possible result of industrial and toxic waste presence. Influent suspended solids, shown on Figure 9, are also of interest since they exhibit a wide range in concentration, with day to day variations as great as 9 to 1.

6.2.1 BOD Removal

BOD removal efficiency was consistently high throughout the period of analysis, with a high degree of data correlation to the prediction equation

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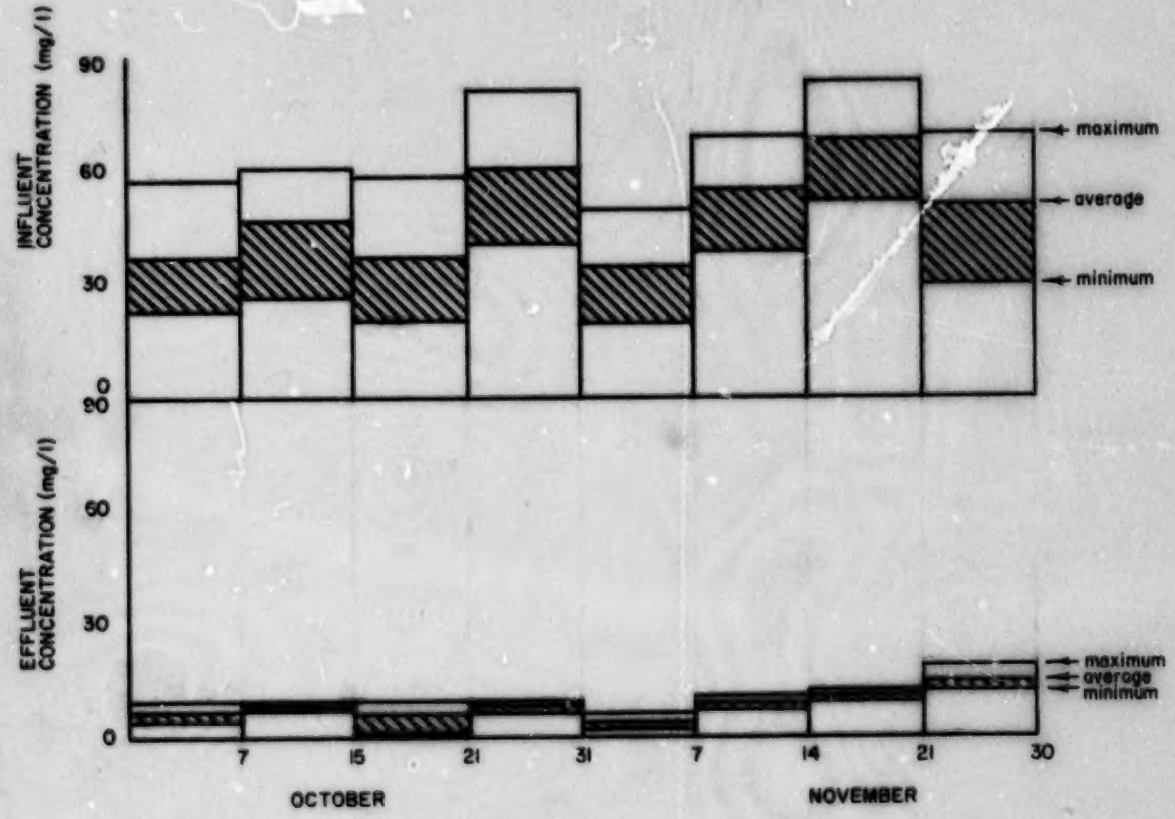

FIGURE 7 INFLUENT AND EFFLUENT BOD October 1 to November 30, 1970

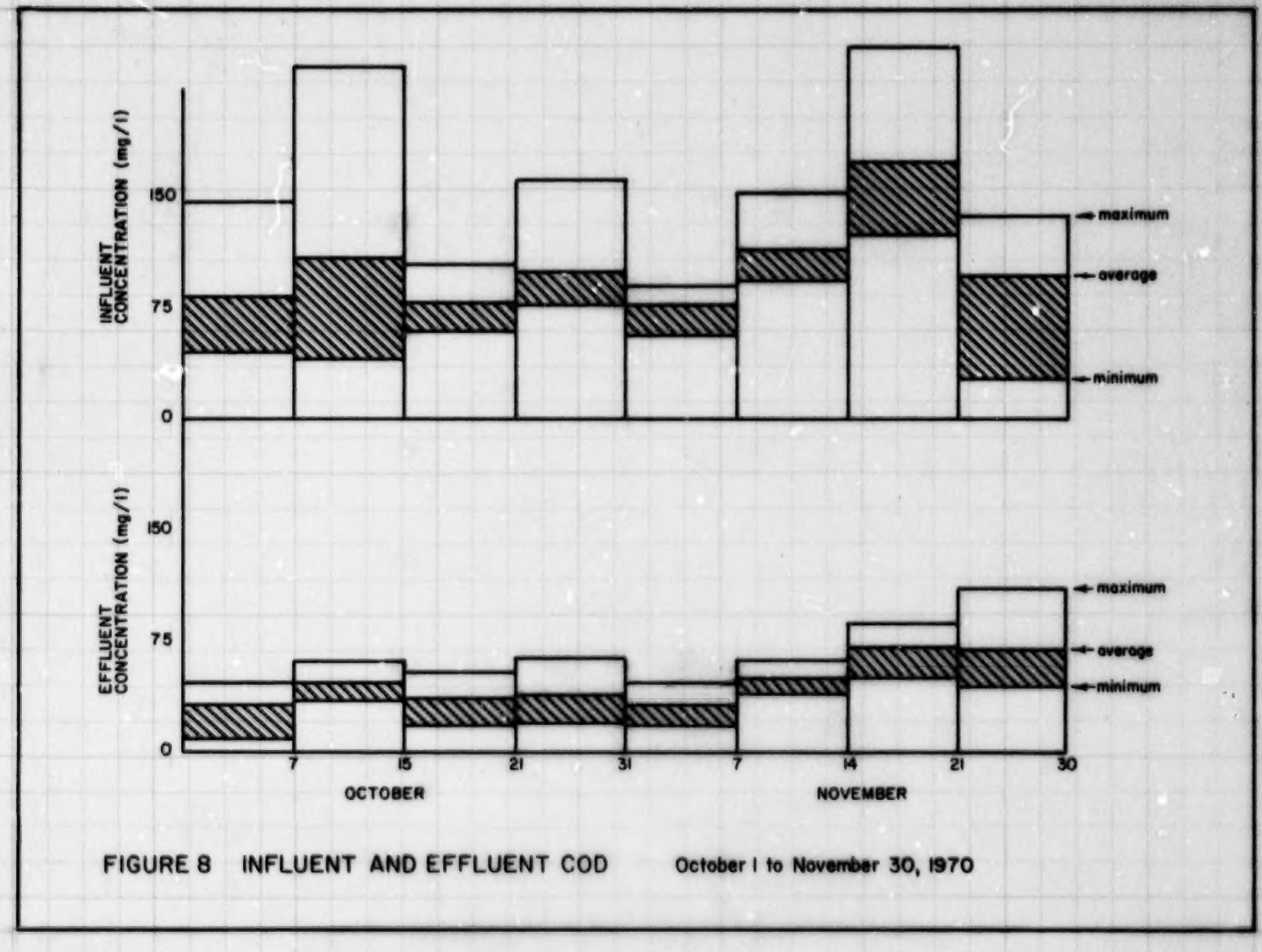

FIGURE 8 INFLUENT AND EFFLUENT COD October 1 to November 30, 1970

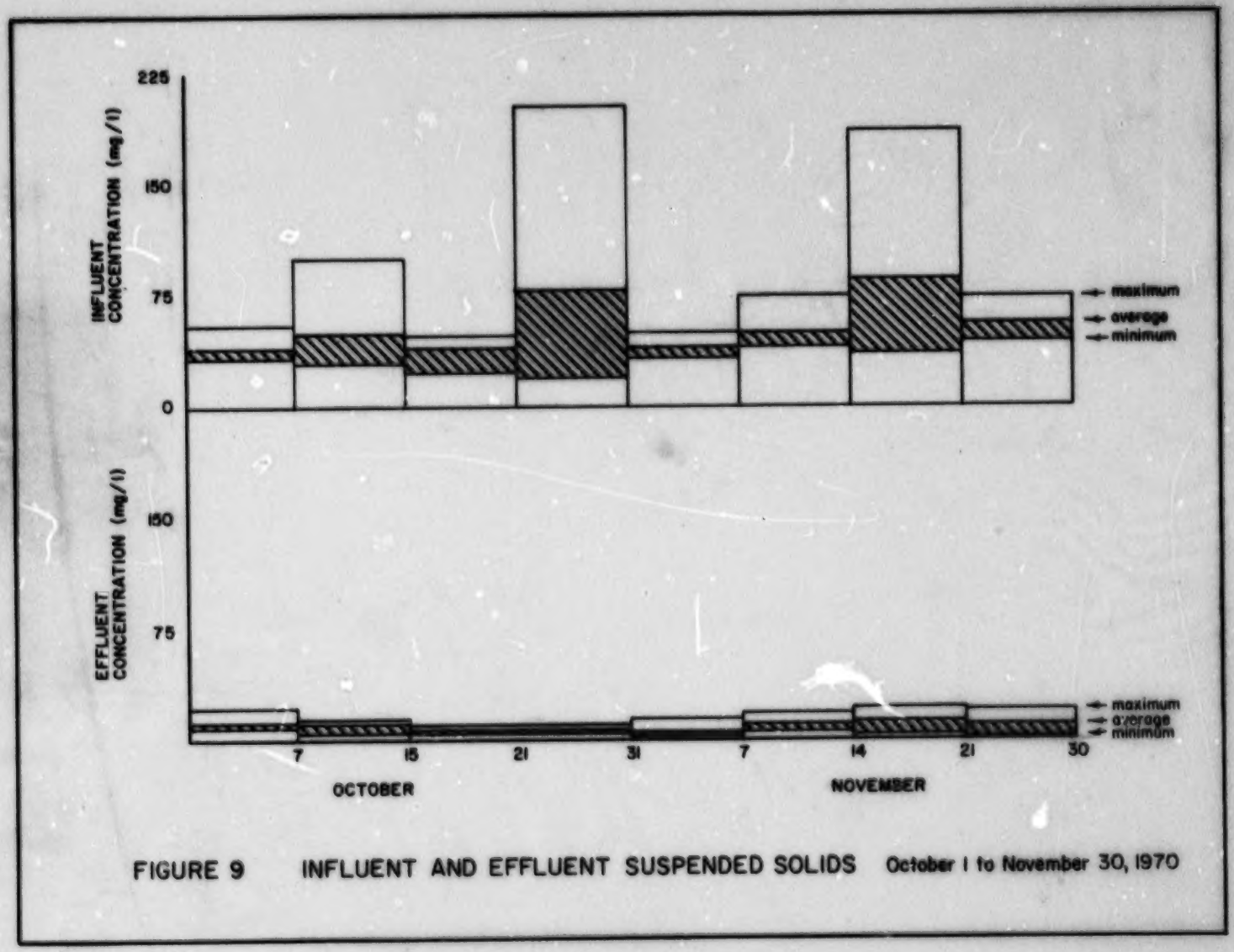

FIGURE 9 INFLUENT AND EFFLUENT SUSPENDED SOLIDS October 1 to November 30, 1970

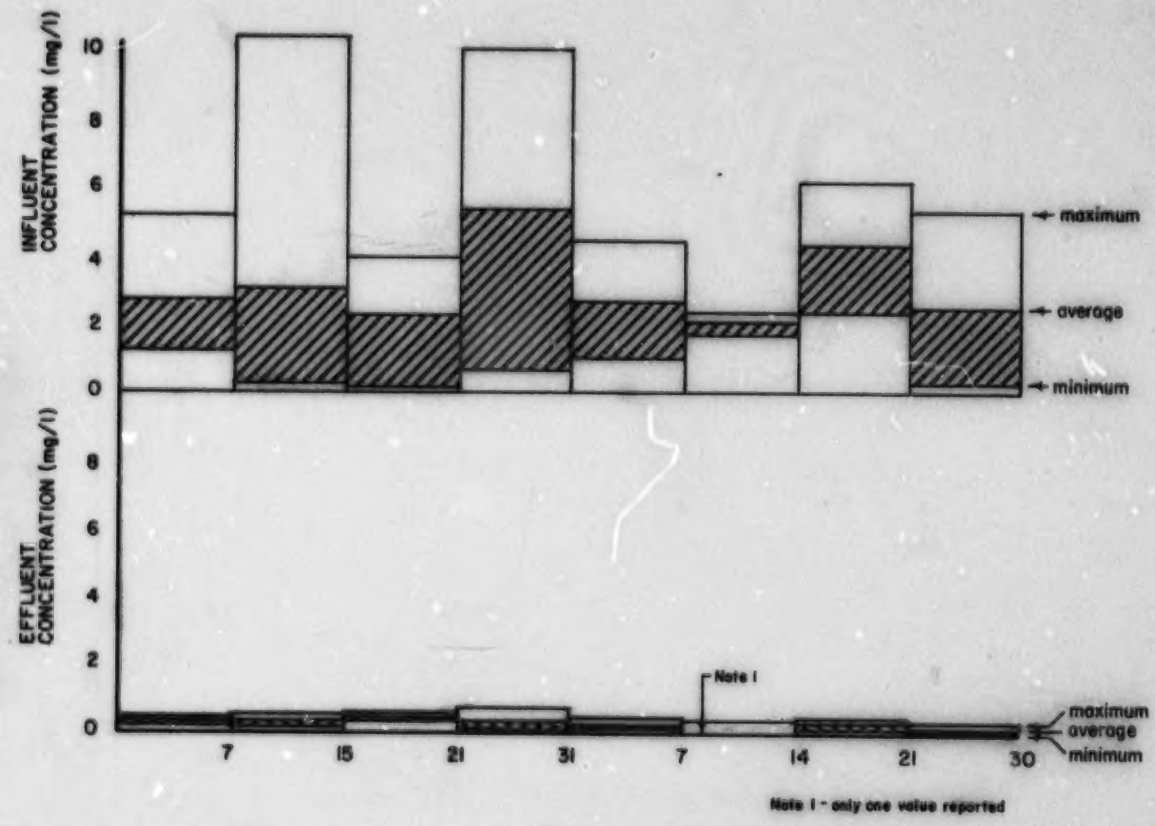

FIGURE 10 INFLUENT AND EFFLUENT $PO_4^{\equiv}$ October 1 to November 30, 1970

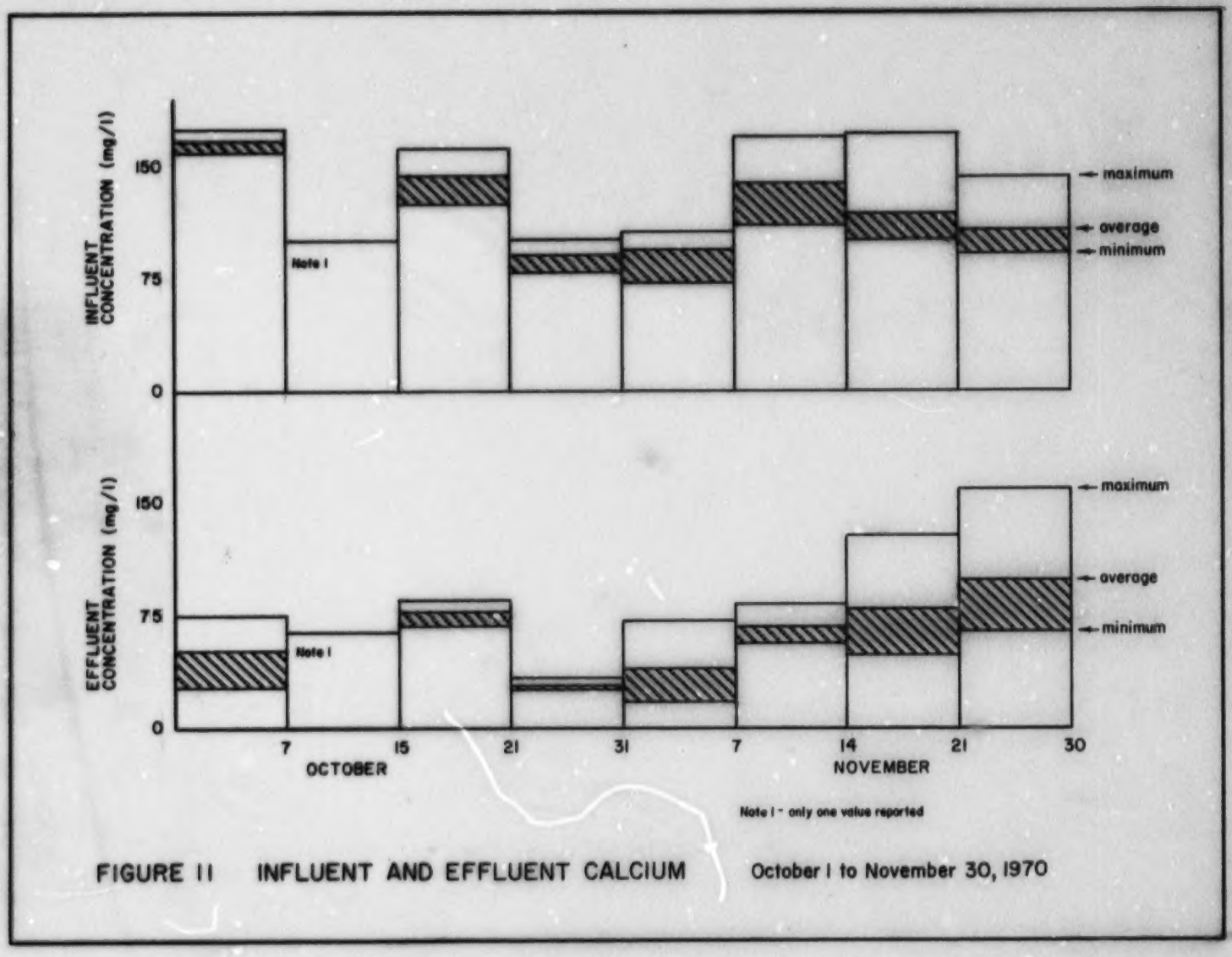

FIGURE II INFLUENT AND EFFLUENT CALCIUM October I to November 30, 1970

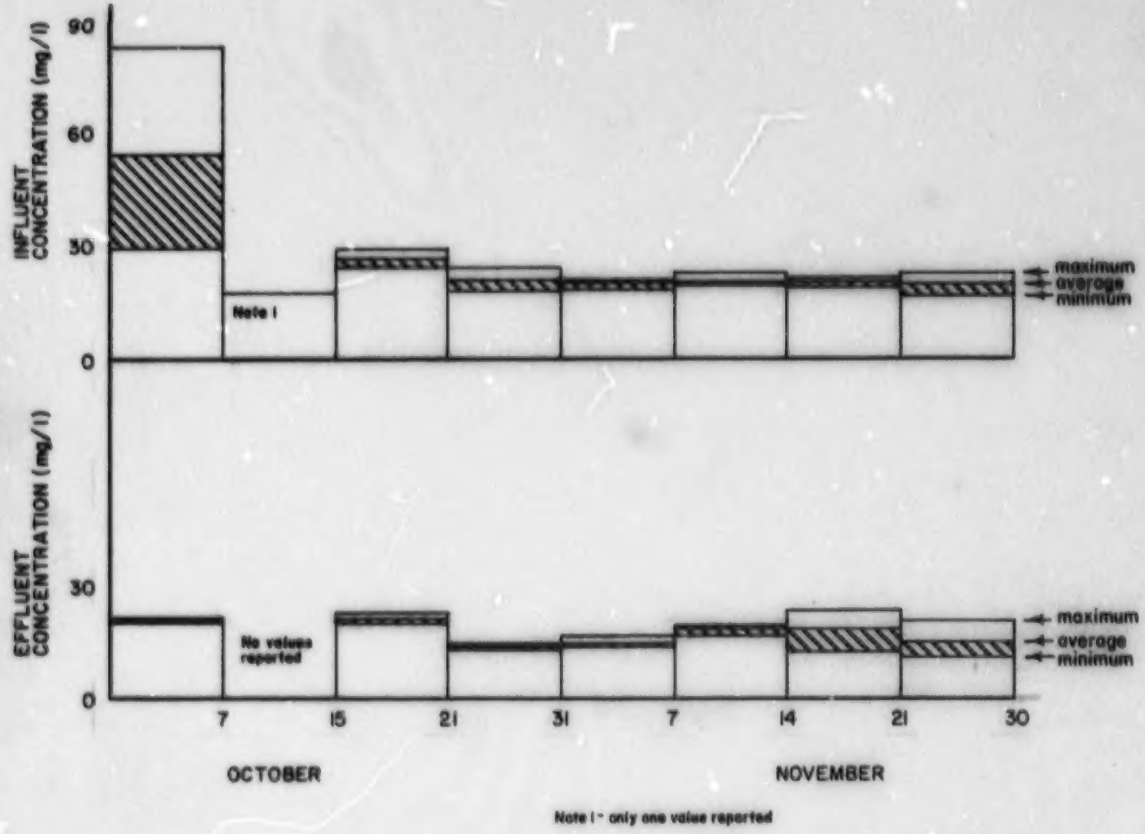

FIGURE 12 INFLUENT AND EFFLUENT MAGNESIUM October 1 to November 30, 1970

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of best fit (r^2=0.92). Removal averaged 82 percent over a range of applied BOD from 30 to 70 mg/l, as shown on Figure 7. The pilot plant consistently produced a treated effluent BOD less than 10 mg/l, except during the last week of the period analyzed when the effluent concentration rose slightly. The predicted efficiency curve (Figure 13) is essentially flat, indicating that the plant was capable of producing good results over a wide range of influent BOD concentrations. This is an important fact, considering that influent to the plant was subject to a wide fluctuation in loading resulting from the variable performance of the preceding biological treatment process.

6.2.2 COD Removal

Influent COD was subject to a 3 to 1 variation ranging from approximately 60 to 180 mg/l. The prediction equation developed for removal efficiency (Figure 14) was shown to have a lower correlation coefficient than that obtained for predicted BOD removal, resulting from a wider variation in the COD removal data values. Removals remained consistently lower for COD than BOD, indicating the possibility of significant amounts of refractory material going untreated. This is most likely due to the poor performance of the activated carbon adsorption process, described in section 6.3. Average plant effluent COD was slightly less than 50 mg/l, significantly greater than the performance goal of 15 mg/l set forth in the original design.

6.2.3 Suspended Solids Removal

Suspended solids removal remained relatively high, averaging 81.2 percent over a wide range of influent values. As shown on Figure 9, influent and effluent suspended solids concentrations indicate that effluent solids levels remained stable over wide ranges of influent variation. Figure 15 is a plot of suspended solids removal vs influent concentration. This can probably be attributed to good floc development in the coagulation process, large enough for almost complete removal in filtration with little breakthrough. Review of the effluent solids data tended to reiterate the point, as indicated by the relatively low turbidity levels. Correlation of the data, with an r^2 of 0.98 for the prediction of removal efficiency, shows slightly increasing removal rates with higher influent loadings.

6.2.4 Turbidity Removal

Turbidity removals, as indicated in Figure 16, were generally high with average values slightly greater than 80 percent, producing average weekly effluent turbidities ranging from approximately 2 to 6 JTU; daily maximum values not exceeding 12 JTU. Average removal efficiency was approximately the same as that reported for suspended solids, although removal remained less consistent for turbidity than for suspended solids. This tends to indicate that removal of colloidal materials, as measured by turbidity, may have been more sensitive to the coagulation and adsorption processes than was suspended solids removal.

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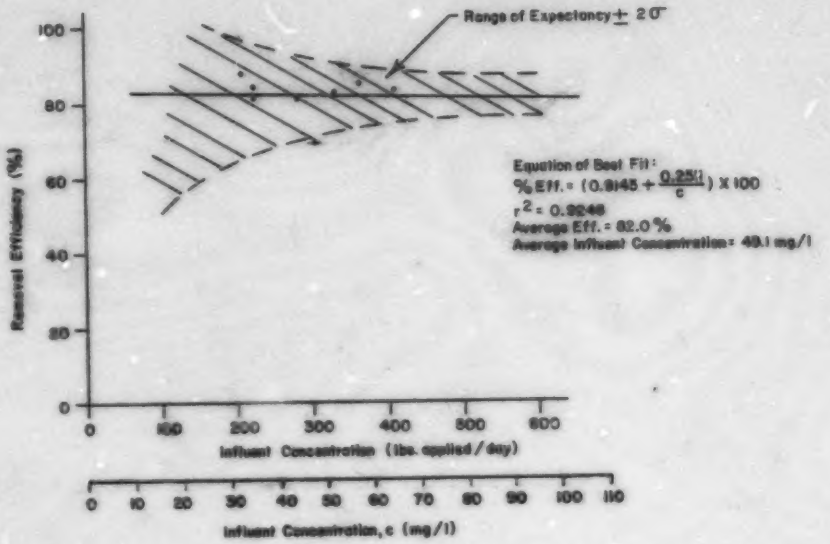
Range of Expectancy ± 2σ
Equation of Best Fit:
% Eff. = (0.9145 + 0.25/c) X 100
r² = 0.9248
Average Eff. = 82.0 %
Average Influent Concentration = 49.1 mg/l
Removal Efficiency (%)
100
80
60
40
20
0
0 100 200 300 400 500 600
Influent Concentration (lbs. applied / day)
0 10 20 30 40 50 60 70 80 90 100 110
Influent Concentration, c (mg/l)

FIGURE 13 BOD_5 REMOVAL

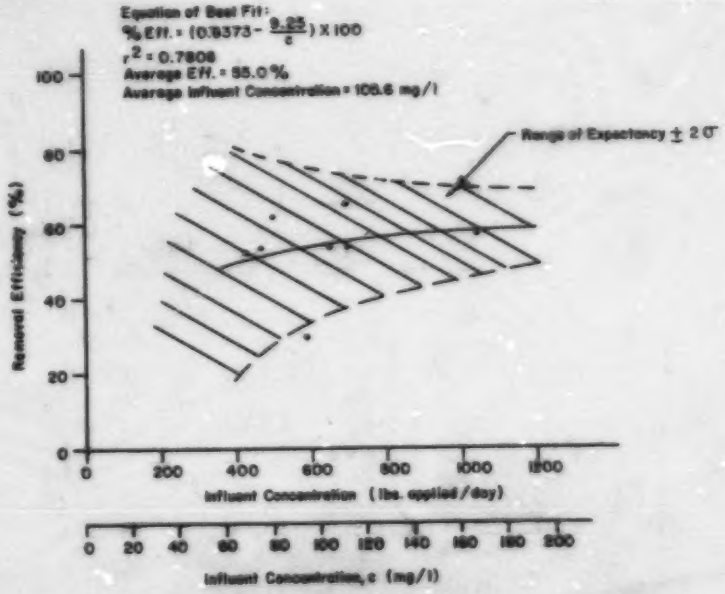
Equation of Best Fit:
% Eff. = (0.9373 - 9.25/c) X 100
r² = 0.7808
Average Eff. = 55.0 %
Average Influent Concentration = 105.6 mg/l
Range of Expectancy ± 2σ
Removal Efficiency (%)
100
80
60
40
20
0
0 200 400 600 800 1000 1200
Influent Concentration (lbs. applied / day)
0 20 40 60 80 100 120 140 160 180 200
Influent Concentration, c (mg/l)

FIGURE 14 COD REMOVAL

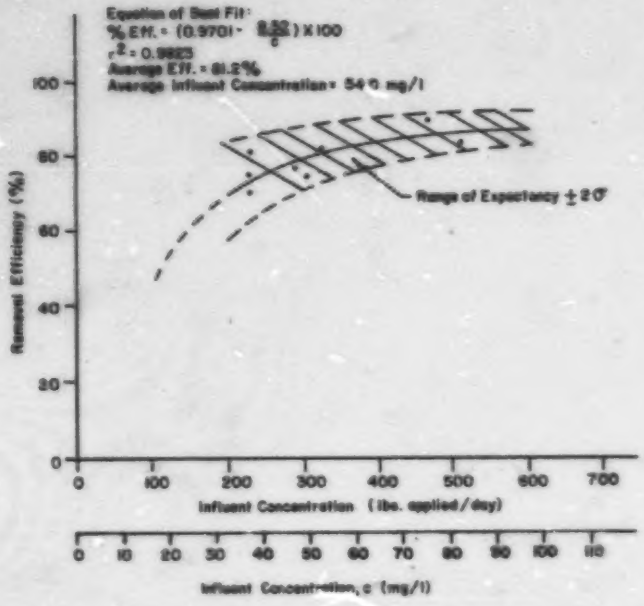

FIGURE 15 SUSPENDED SOLIDS REMOVAL

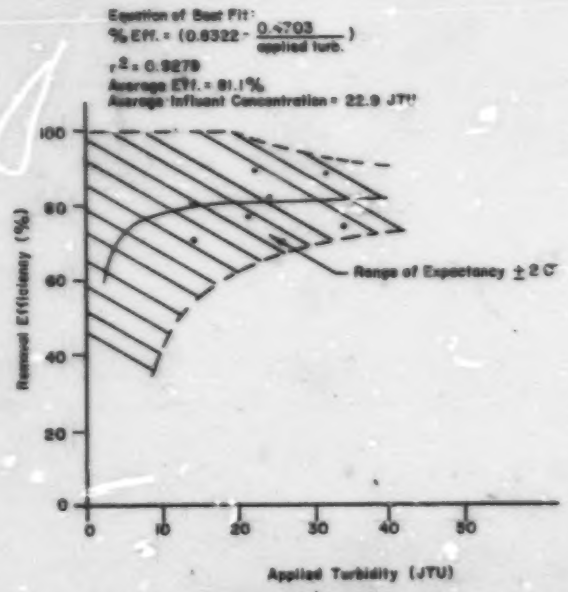

FIGURE 16 TURBIDITY REMOVAL

6.2.5 Phosphate Removal

Treatment for removal of phosphates proved highly successful with an average overall removal efficiency (Figure 17) slightly greater than 90 percent. The degree of data fit given by the prediction equation was high, with r^2=0.98. The average influent concentration was approximately 3.2 mg/l with a corresponding average effluent concentration of 0.30 mg/l, well below the generally accepted value of 1.0 mg/l considered necessary to limit algal growth in the Great Lakes. The high degree of phosphate removal most likely stems from the application of lime in excess of that necessary to produce hydroxyapatite precipitation.

6.2.6 Calcium Removal

Removal of calcium fluctuated widely throughout the analysis period with average removal efficiencies ranging from 10 to 70 percent. The relationship between average influent and effluent concentrations showed a low correlation, with r^2=0.46, a result of the data scatter shown on Figure 18. Because of this fact, the expectation of data ($\pm 2\sigma$) is unlimited over efficiency, showing low confidence in predicted calcium removal.

Calcium removal is largely the result of softening, which occurs when lime reacts with influent calcium to form insoluble calcium carbonate in the presence of carbonate alkalinity. The fluctuation in effluent calcium indicates that lime softening in the solids contact process was highly variable, dependent upon lime dosage and influent calcium hardness. High removals are the result of reacting just enough lime to produce a maximum level of carbonate alkalinity. Insufficient or excess addition of lime will cause influent or lime-associated calcium to remain in solution, leaving high levels of calcium remaining in the effluent. Since pH following solids contact generally remained below 10, the value at which carbonate alkalinity reaches its maximum, it is thought that effluent calcium is largely the result of unremoved influent hardness.

6.2.7 Magnesium Removal

In general, magnesium removals were low (Figure 19), since the quantity of lime added in the solids contact process was insufficient to form the hydroxyl alkalinity necessary for the precipitation of insoluble magnesium hydroxide (Brucine). Typical removals were from 10 to 35 percent with only one week averaging approximately 60 percent. Due to relatively low influent magnesium concentrations, removal of magnesium was not of great significance in the overall performance of the pilot plant.

6.2.8 Total Dissolved Solids Removal

Concentrations of total dissolved solids remained appreciable throughout the treatment process, with an average overall removal efficiency of approximately 15 percent, as shown in Figure 20. The correlation between influent and effluent was low, as can be seen from the data scatter shown in Figure 14. The low efficiency and high degree of variability can be

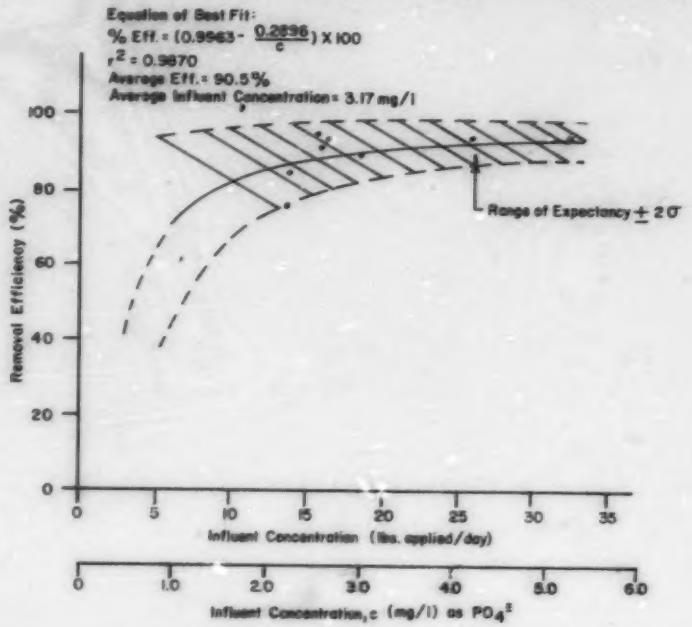
Equation of Best Fit:
% Eff. = (0.9963 - 0.2696/c) X 100
r² = 0.9870
Average Eff. = 90.5%
Average Influent Concentration = 3.17 mg/l
Removal Efficiency (%)
Range of Expectancy ± 2σ
Influent Concentration (lbs. applied/day)
Influent Concentration, c (mg/l) as PO4³

FIGURE 17 PHOSPHATE REMOVAL

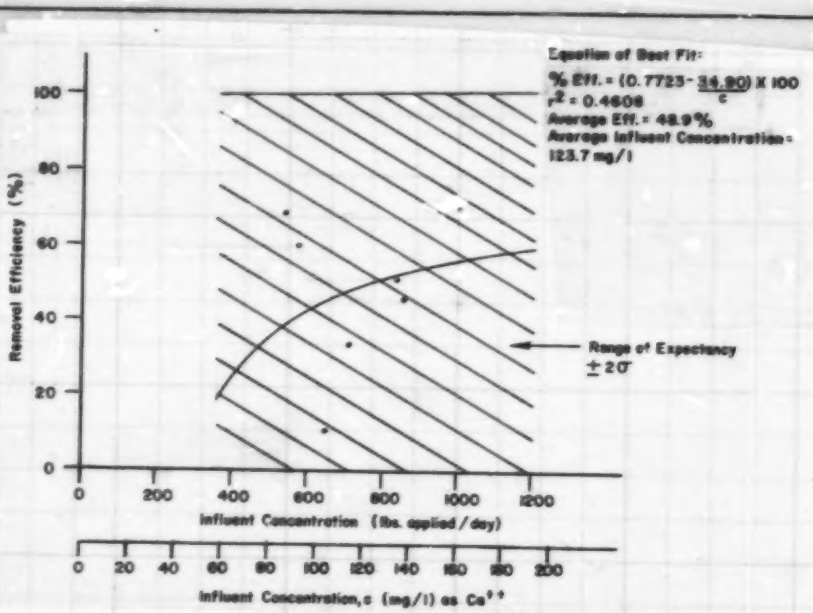
Equation of Best Fit:
% Eff. = (0.7725 - 34.90/c) X 100
r² = 0.4608
Average Eff. = 48.9%
Average Influent Concentration = 123.7 mg/l
Removal Efficiency (%)
Range of Expectancy ± 2σ
Influent Concentration (lbs. applied/day)
Influent Concentration, c (mg/l) as Ca⁺⁺

FIGURE 18 CALCIUM REMOVAL

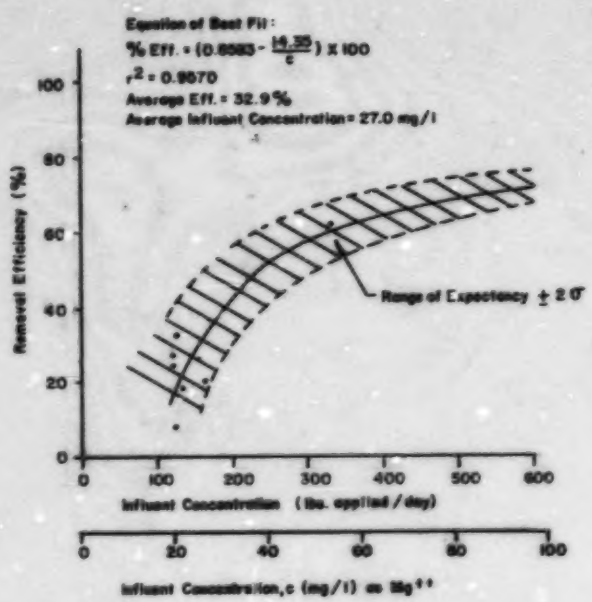
Equation of Best Fit:
% Eff. = (0.8583 - 14.35/c) X 100
r² = 0.9870
Average Eff. = 32.9 %
Average Influent Concentration = 27.0 mg/l
Removal Efficiency (%)
Range of Expectancy ± 2 σ
Influent Concentration (lbs. applied / day)
Influent Concentration, c (mg/l) as Mg++

FIGURE 19 MAGNESIUM REMOVAL

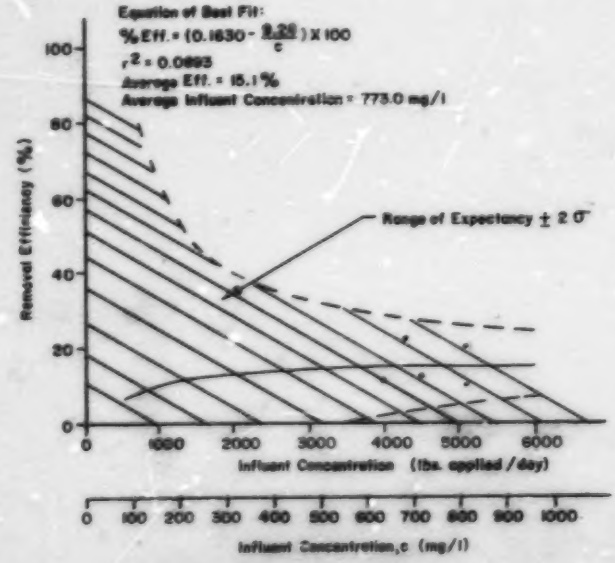
Equation of Best Fit:
% Eff. = (0.1630 - 9.26/c) X 100
r² = 0.0893
Average Eff. = 15.1 %
Average Influent Concentration = 773.0 mg/l
Removal Efficiency (%)
Range of Expectancy ± 2 σ
Influent Concentration (lbs. applied / day)
Influent Concentration, c (mg/l)

FIGURE 20 TOTAL DISSOLVED SOLIDS REMOVAL

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expected from the treatment processes employed, since selective removal of mineral solids was not practiced. If the treated effluent were to be used as manufacturing or process water, solids buildup might be a significant concern, requiring ion exchange or other demineralization processes.

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6.3 Carbon Treatment

The theory behind and purposes of activated carbon treatment were summarily described in Chapter 4. The carbon treatment process included in the pilot study deserves special comment since results obtained from adsorption were somewhat disappointing.

The principal purpose of carbon treatment was for removal of long-chained refractory organics and hydrophilic solvents contained in domestic and in manufacturing, chemical and process industry wastes. Activated carbon treatment was incorporated into the pilot plant design because heavy industrial development at East Chicago led to significant contributions of these materials in the applied waste load.

In the review of analytical data generated during the course of the pilot study, activated carbon adsorption was shown to be the weak link in the process chain. The results of the analysis of carbon treatment are seen in the low degree of performance in the removal of BOD and COD, shown in Table 5. BOD remained essentially unchanged through carbon treatment, while overall average reduction of COD fell below 30 percent. Removals of either constituent, BOD or COD, were highly inconsistent from week to week, and a comparison of the two in any one week period shows only a slight trend between them.

The poor carbon performance is difficult to comprehend, although several explanations can be considered. The first of these holds that carbon capacity may have reached exhaustion prematurely due to heavy organic loading. This possibility can be ruled out if it is assumed that the carbon exhibited a typical adsorptive capacity of 0.5 gm COD/gm Carbon, since total applied COD up until the analysis period fell far below that level. Another hypothesis assumed the formation of an impenetrable calcium carbonate scale on the granular carbon surface, removing much of the interstitial surface area from contact with the waste solution. It is unlikely that carbonate scaling occurred to a significant extent, since sulphuric acid neutralization would have reduced carbonate alkalinity levels below those necessary to promote calcium carbonate precipitation.

Two further explanations remained beyond those considered above, each of which would have resulted in the sealing of the carbon pore structure. They are: 1) surface coating by another chemical precipitant, and 2) incompatibility of the characteristic carbon pore size with molecular sizes of the COD related contaminants, resulting in the collection of high molecular weight compounds at the carbon surface. Should either of these conditions have existed, the effective surface area would have been greatly reduced, causing minimal adsorption. It is felt that either one or both of these phenomena may have occurred, offering the best explanation for poor carbon performance.

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TABLE 5: ACTIVATED CARBON TREATMENT PERFORMANCE
For Removal of BOD and COD -- October 1 through November 30, 1970

	10/1-7	10/8-15	10/16-21	10/22-31	11/1-7	11/8-14	11/15-21	11/22-30	Avg.
BOD									
influent (mg/l)	9.38	7.52	4.57	8.96	2.23	10.64	11.50	14.03	8.60
effluent (mg/l)	6.67	8.56	6.29	8.56	3.98	9.75	11.48	15.47	8.84
% Removal	28.8	*	*	4.5	*	8.4	0.17	*	*
COD									
influent (mg/l)	44.08	56.30	63.38	59.37	39.63	78.54	104.50	95.03	67.60
effluent (mg/l)	30.95	48.35	37.13	39.52	32.70	49.86	72.30	69.72	47.56
% Removal	29.8	14.1	41.4	33.4	17.5	36.5	30.8	26.6	29.6

Note: * indicates increase in effluent concentration over infiuent concentration.

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CHAPTER 7

OPERATING COST DATA

One of the principal objectives of the study was the determination of labor requirements and operating costs associated with the use of the physical-chemical treatment process. To this end, daily operating data was collected for the following items:

1) Running hours
2) Lime consumption
3) Ferric chloride consumption
4) Operation man-hours
5) Chemical preparation man-hours
6) Maintenance man-hours

For 24 hour-per-day operation, electrical consumption was estimated to amount to 625 kwh/day, principally representing pumping costs associated with low lift pumping to the Densator and booster pumping of filtered effluent to the carbon columns. Hydrated lime consumption during October and November 1970 varied from 785 kg/day (1729 lb/day) to 1064 kg/day (2344 lb/day), averaging 931 kg/day (2051 lb/day). During the same period, ferric chloride was used intermittantly at a consumption rate of 45.4 kg/day (100 lb/day). Since plant scale-up would most likely employ pH adjustment by means other than acid addition (e.g., recarbonation by stack gas or carbon dioxide), consumption of neutralization acid was not reported.

Daily labor records indicate that approximately 5 hours were spent on routine plant operations, 3 hours were spent on preparation of chemical solutions and less than 1 hour was spent on maintenance of plant equipment.

Table 6 reflects the above and gives estimates of operating costs for the processing of 2840 m^3/day (0.75MGD). All costs are based upon current (Dec. 1978) prices (ENR Construction Cost Index = 2868.50).

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TABLE 6:

OPERATION AND MAINTENANCE COSTS

Electrical	$/1000 gal	$/yr (@ 0.75 mgd)
625 kwh/day @ $0.030/kwh	0.025	$ 6,850.
Chemicals		
Lime - 2051 lb/day @ $0.0373/lb	0.102	28,000.
Ferric Chloride - 100 lb/day @ $0.0392/lb	0.005	1,450.
Total Chemical Costs	0.107	29,450.
Labor		
Plant Operations - 5 hr/day @ $9.10/hr	0.061	16,600.
Chemical preparation - 3 hr/day @ $6.20/hr	0.025	6,800.
Maintenance - 1 hr/day @ $8.20/hr	0.011	3,000.
Total Labor & Maintenance	0.097	26,400.
Total Operations and Maintenance Costs*	0.229	$62,700.

* Does not include neutralization costs - refer to text.

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5. Upper Mississippi River Board of State Sanitary Engineers, "Recommended Standards for Water Works," 1968 edition.

6. Culp, R.L. and Culp, G.L., Advanced Wastewater Treatment, Van Nostrand Reinhold Co., New York, 1971.

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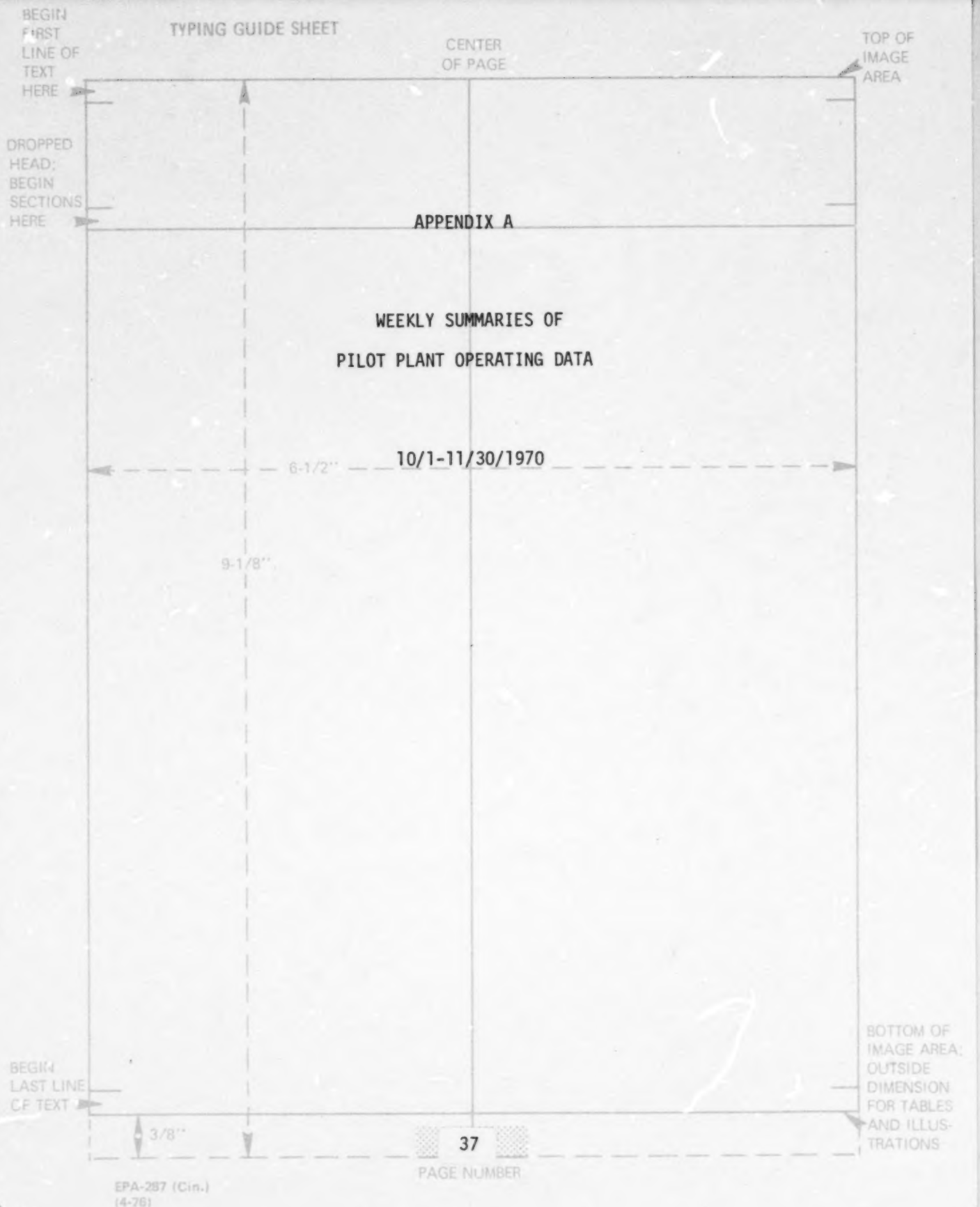
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APPENDIX A
WEEKLY SUMMARIES OF
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TABLE A1: PILOT PLANT OPERATING DATA FOR THE WEEK OF 10/1-10/7

		Influent	Following Densator		Following Filtration		Following Activated Carbon Adsorption	
		mg/l	mg/l	% Removal	mg/l	% Removal	mg/l	% Removal
Suspended Solids	Avg	38.80	47.4	-16.4	9.6	74.88	11.2	68.63
	Min	32.00	31.0	-37.25	4.0	63.64	8.0	31.25
	Max	55.00	64.0	6.06	12.0	87.50	22.0	85.45
BOD_5	Avg	37.40	7.19	78.53	9.38	71.81	6.67	80.64
	Min	23.20	3.16	64.55	7.24	62.01	4.06	71.43
	Max	58.60	10.10	92.60	10.6	83.04	8.48	88.27
PO_4	Avg	2.75	.40	79.33	.27	86.27	.17	91.78
	Min	1.26	.16	55.56	.18	73.02	.13	88.73
	Max	4.87	.56	92.49	.34	94.25	.24	96.92
C.O.D.	Avg	82.96	71.78	11.89	44.08	43.90	30.95	61.98
	Min	45.00	41.50	-42.35	25.70	17.56	8.36	33.48
	Max	144.90	115.00	41.80	68.00	63.96	47.00	81.42
Total Hardness (as $CaCO_3$)	Avg	548.60	317.05	42.27	319.58	41.03	310.50	43.17
	Min	488.10	198.9	30.63	262.20	26.96	284.30	37.76
	Max	594.00	385.1	61.95	356.50	55.52	336.4	49.80
Alkalinity (as $CaCO_3$)	Avg	373.94	140.48	62.15	82.06	78.01	76.52	79.52
	Min	280.30	98.70	51.61	65.40	74.42	58.10	77.98
	Max	419.10	195.00	74.57	107.20	80.86	92.3	82.31
pH*	Avg	7.95	9.42		7.79		7.31	
	Min	7.61	8.92		7.64		7.20	
	Max	8.13	10.34		7.84		7.38	
Turbidity**	Avg	22.00	25.67	-16.59	2.93	85.32	1.97	91.01
	Min	16.00	22.00	-34.62	2.30	79.41	1.5	90.63
	Max	33.00	29.00	12.12	3.50	90.91	2.90	91.21
Calcium	Avg	167.50	52.50	69.15	49.50	71.07	51.50	69.82
	Min	160.00	32.00	58.29	24.00	57.14	28.00	57.14
	Max	175.00	73.00	80.00	75.00	85.00	75.00	82.50
Magnesium	Avg	55.55	23.4	45.97	22.95	46.85	21.40	49.74
	Min	29.10	23.0	20.96	22.70	21.99	21.00	25.09
	Max	82.00	23.8	70.98	23.20	71.71	21.80	74.39
T.D.S.	Avg	862.50	696.50	19.28	697.00	19.31	688.50	20.27
	Min	802.00	612.00	13.16	618.00	13.94	596.00	13.90
	Max	904.00	752.00	25.00	778.00	22.94	756.00	25.69

% indicates percent removal over influent

* as $-\log_{10}(H^+)$

** as JTU

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TABLE A2: PILOT PLANT OPERATING DATA FOR THE WEEK OF 10/8-10/15

		Influent	Following Densator		Following Filtration		Following Activated Carbon Adsorption	
		mg/l	mg/l	% Removal	mg/l	% Removal	mg/l	% Removal
Suspended Solids	Avg	50.67	41.00	10.84	11.33	70.76	12.25	68.06
	Min	29.00	23.00	-50.00	1.00	24.14	5.00	48.28
	Max	100.00	58.00	68.00	22.00	97.06	15.00	95.00
BOD_5	Avg	47.32	6.58	73.91	7.52	85.41	8.56	84.45
	Min	26.80	0.01	78.73	0.01	75.82	8.08	81.67
	Max	66.50	10.70	99.97	11.20	99.97	9.22	87.26
PO_4	Avg	3.09	0.35	66.21	0.11	95.93	0.32	46.55
	Min	0.20	0.01	-28.95	0.01	91.50	0.01	-51.79
	Max	10.70	0.74	95.00	0.25	99.56	0.56	96.45
C.O.D.	Avg	107.98	77.47	18.91	56.30	39.51	48.35	59.07
	Min	40.70	16.60	-45.75	23.50	17.10	36.50	43.08
	Max	239.00	143.60	77.32	88.70	75.90	60.90	76.74
Total Hardness (as $CaCO_3$)	Avg	534.95	306.13	41.81	292.68	45.27	362.20	37.05
	Min	434.70	203.40	17.90	196.90	22.59	237.50	15.37
	Max	621.70	437.50	67.28	412.50	63.11	512.20	61.80
Alkalinity (as $CaCO_3$)	Avg	312.08	121.30	62.82	89.20	70.48	103.10	69.36
	Min	195.6	56.10	48.80	51.90	62.90	82.40	63.35
	Max	408.30	204.80	72.53	148.40	79.06	146.60	79.08
pH*	Avg	8.01	9.49		8.49		7.38	
	Min	7.63	8.95		7.31		7.27	
	Max	8.80	10.36		10.42		7.48	
Turbidity**	Avg	23.67	16.25	27.73	4.08	79.89	4.05	79.16
	Min	12.00	13.00	-40.91	2.4	50.77	3.6	65.38
	Max	51.00	22.00	66.67	6.4	91.43	4.5	92.94
Calcium	Avg	101.00	79.00	21.78	65.00	35.64	-	-
	Min							
	Max							
Magnesium	Avg	18.00	13.40	25.56	13.00	27.78	-	-
	Min							
	Max							
T.D.S.	Avg	666.00	495.20	18.82	552.80	9.94	589.33	28.64
	Min	238.00	318.00	-25.16	352.00	-32.39	528.00	19.62
	Max	846.00	744.00	48.09	734.00	40.19	680.00	36.84

% indicates percent removal over influent

* as $-\log_{10}(H^+)$

** as JTU

TABLE A3: PILOT PLANT OPERATING DATA FOR THE WEEK OF 10/16-10/21

		Influent	Following Densator		Following Filtration		Following Activated Carbon Adsorption	
		mg/l	mg/l	% Removal	mg/l	% Removal	mg/l	% Removal
Suspended Solids	Avg	38.75	44.75	-8.70	9.75	70.92	9.67	70.60
	Min	24.00	17.00	-57.14	6.00	41.67	8.00	50.00
	Max	47.00	56.00	63.83	14.00	87.23	12.00	80.95
BOD_5	Avg	37.60	3.81	88.68	4.57	85.38	6.29	78.37
	Min	21.20	0.01	76.01	0.01	66.70	0.01	57.03
	Max	59.00	10.70	99.98	11.20	99.98	9.76	99.96
PO_4	Avg	2.29	0.28	87.82	0.21	54.43	0.55	4.01
	Min	0.14	0.11	78.39	0.14	-22.22	0.44	-68.18
	Max	4.00	0.59	97.25	0.30	96.50	0.65	76.19
C.O.D.	Avg	79.60	56.65	27.79	63.38	20.83	37.13	51.79
	Min	60.00	30.10	-6.83	30.30	-35.34	19.20	39.33
	Max	105.00	77.90	51.69	92.80	51.36	55.80	69.18
Total Hardness (as $CaCO_3$)	Avg	573.28	398.23	30.54	388.13	32.53	392.87	31.73
	Min	538.10	313.90	20.64	261.40	22.44	347.10	24.24
	Max	625.80	447.90	44.42	485.40	53.72	427.60	35.50
Alkalinity (as $CaCO_3$)	Avg	365.50	179.68	49.39	134.35	63.76	131.27	62.48
	Min	291.10	108.20	-0.22	25.50	16.90	23.80	23.44
	Max	464.80	357.00	76.72	296.00	91.24	272.70	91.82
pH*	Avg	7.98	9.40		8.31		7.28	
	Min	7.82	8.20		7.57		6.96	
	Max	8.23	10.25		10.01		7.47	
Turbidity**	Avg	14.05	23.25	-31.30	9.85	37.38	4.13	62.10
	Min	7.00	10.00	-73.55	1.40	-40.00	2.70	48.78
	Max	23.00	31.00	56.52	30.00	93.91	5.50	76.09
Calcium	Avg	144.00	85.5	39.29	68.50	50.93	78.00	45.77
	Min	126.00	81.00	28.57	60.00	38.89	69.00	45.24
	Max	162.00	90.00	50.00	77.00	62.96	87.00	46.30
Magnesium	Avg	27.50	27.20	0.81	26.30	3.86	22.00	19.24
	Min	25.60	26.60	-7.91	25.30	-6.23	20.50	8.20
	Max	29.40	27.80	9.52	27.30	13.95	23.50	30.27
T.D.S.	Avg	852.00	714.67	15.77	753.33	11.37	770.00	6.33
	Min	822.00	658.00	1.70	734.00	6.08	748.00	3.65
	Max	912.00	808.00	25.66	772.00	17.32	792.00	9.00

% indicates percent removal over influent

* as $-\log_{10}(H^+)$

** as JTU

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TABLE A4: PILOT PLANT OPERATING DATA FOR THE WEEK OF 10/22-10/31

		Influent	Following Densator		Following Filtration		Following Activated Carbon Adsorption	
		mg/l	mg/l	% Removal	mg/l	% Removal	mg/l	% Removal
Suspended Solids	Avg	77.60	30.60	33.14	7.40	84.59	7.20	83.09
	Min	24.00	19.00	-11.11	1.00	70.00	4.00	66.67
	Max	202.00	44.00	83.17	13.00	98.80	10.00	96.53
BOD_5	Avg	60.48	9.25	83.41	8.96	84.16	8.56	85.15
	Min	41.40	5.32	80.50	6.84	76.43	6.56	79.61
	Max	81.90	11.00	93.50	10.50	89.89	10.10	89.43
PO_4	Avg	5.41	0.94	83.23	0.51	91.44	0.37	93.58
	Min	0.70	0.75	72.49	0.37	89.72	0.[illegible]	85.01
	Max	10.20	1.45	92.65	0.74	95.98	0.79	98.14
C.O.D.	Avg	115.18	70.02	36.46	59.37	44.76	39.52	64.70
	Min	76.40	35.50	-34.14	33.70	-32.39	19.90	38.22
	Max	163.00	116.00	67.43	113.00	66.23	65.00	80.06
Total Hardness (as $CaCO_3$)	Avg	478.40	319.83	32.99	303.78	36.80	300.38	36.39
	Min	321.60	215.70	24.99	198.00	30.61	223.70	29.97
	Max	573.30	412.10	41.29	397.80	39.06	339.00	43.73
Alkalinity (as $CaCO_3$)	Avg	342.20	132.32	61.10	48.05	85.92	58.80	82.59
	Min	278.40	106.00	53.80	16.60	72.70	40.10	75.50
	Max	411.00	146.10	69.83	76.00	94.75	78.80	89.28
pH*	Avg	7.83	9.80		7.14		7.11	
	Min	7.62	9.49		6.19		6.77	
	Max	8.00	10.05		8.23		7.65	
Turbidity**	Avg	31.50	13.00	41.35	3.33	86.11	3.50	85.71
	Min	11.00	12.00	-15.38	2.50	75.45	2.50	75.45
	Max	65.00	15.00	76.92	4.70	92.77	5.20	92.00
Calcium	Avg	91.00	35.50	59.34	34.00	62.07	29.00	66.83
	Min	79.00	29.00	46.84	26.00	49.37	24.00	56.96
	Max	103.00	42.00	71.84	40.00	74.76	34.00	76.70
Magnesium	Avg	21.35	14.40	32.43	13.75	35.30	14.60	30.48
	Min	18.40	12.60	31.52	12.30	33.15	14.30	22.28
	Max	24.30	16.20	33.33	15.20	37.45	14.90	38.68
T.D.S.	Avg	720.50	524.50	27.51	638.50	11.04	561.50	22.19
	Min	656.00	410.00	23.56	596.00	1.52	474.00	15.76
	Max	832.00	632.00	37.50	704.00	15.38	654.00	21.39

% indicates percent removal over influent

* as $-\log_{10}(H^+)$

** as JTU

TABLE A5: PILOT PLANT OPERATING DATA FOR THE WEEK OF 11/1-11/7

		Influent	Following Densator		Following Filtration		Following Activated Carbon Adsorption	
		mg/l	mg/l	% Removal	mg/l	% Removal	mg/l	% Removal
Suspended Solids	Avg	38.75	40.00	-3.11	7.75	82.50	6.75	84.70
	Min	32.00	29.00	-9.43	1.00	58.33	1.00	68.75
	Max	48.00	53.00	9.38	20.00	96.97	15.00	96.97
BOD_5	Avg	35.45	3.17	93.10	2.23	95.09	3.98	87.20
	Min	20.10	0.01	85.71	0.01	89.23	2.56	78.27
	Max	50.10	7.16	99.97	4.48	99.97	6.52	94.85
PO_4	Avg	2.68	0.60	71.91	0.38	82.43	0.24	85.60
	Min	1.13	0.34	41.59	0.21	63.72	0.01	63.72
	Max	4.60	0.78	83.04	0.56	89.50	0.41	99.67
C.O.D.	Avg	71.33	50.70	28.72	39.63	42.19	32.70	54.03
	Min	57.50	43.00	25.22	26.40	26.23	17.60	37.04
	Max	90.00	63.40	32.17	50.90	70.67	48.00	74.42
Total Hardness (as $CaCO_3$)	Avg	362.05	212.50	42.01	204.25	44.07	220.40	39.29
	Min	345.70	146.40	26.37	156.70	33.46	197.00	35.57
	Max	378.40	278.6	57.65	251.80	54.67	243.80	43.01
Alkalinity (as $CaCO_3$)	Avg	303.80	156.20	46.59	82.20	71.81	81.18	72.08
	Min	245.20	112.90	27.20	40.90	59.54	55.00	61.62
	Max	285.70	181.80	62.32	105.70	86.35	102.30	81.64
pH*	Avg	7.70	9.81		7.56		7.37	
	Min	7.53	9.48		6.95		7.03	
	Max	7.90	9.99		7.90		7.53	
Turbidity**	Avg	13.75	16.50	-19.57	3.55	72.42	2.7	79.29
	Min	11.00	16.00	-31.25	3.30	65.45	2.7	75.45
	Max	16.00	17.00	-5.88	3.80	79.38	2.7	83.13
Calcium	Avg	96.25	39.75	59.53	35.75	64.05	39.25	60.78
	Min	73.00	23.00	36.45	17.00	41.12	17.00	41.12
	Max	107.00	68.00	76.53	63.00	82.65	63.00	82.65
Magnesium	Avg	20.53	16.08	21.62	15.75	23.20	15.70	23.39
	Min	18.80	14.70	13.04	14.40	14.01	14.60	14.98
	Max	21.30	18.00	25.82	17.80	28.17	17.60	31.46
T.D.S.	Avg	765.00	600.00	22.12	697.50	9.37	673.00	12.59
	Min	702.00	500.00	15.46	590.00	2.78	566.00	5.80
	Max	828.00	700.00	28.77	805.00	15.95	780.00	19.37

% indicates percent removal over influent

* as $-\log_{10}(H^+)$

** as JTU

TABLE A6: PILOT PLANT OPERATING DATA FOR THE WEEK OF 11/8-11/14

		Influent	Following Densator		Following Filtration		Following Activated Carbon Adsorption	
		mg/l	mg/l	% Removal	mg/l	% Removal	mg/l	% Removal
Suspended Solids	Avg	48.25	57.25	-16.78	10.25	78.25	11.25	76.85
	Min	39.00	48.00	-38.46	5.00	67.23	5.00	69.23
	Max	74.00	65.00	35.14	14.00	87.50	18.00	87.50
BOD_5	Avg	55.35	10.87	79.48	10.64	79.67	9.75	81.52
	Min	39.10	9.56	71.61	7.42	71.36	7.74	74.17
	Max	69.70	12.40	85.15	12.30	88.51	11.50	87.32
PO_4	Avg	2.15	1.29	46.25	0.62	74.17	0.34	85.83
	Min	1.9						
	Max	2.4						
C.O.D.	Avg	115.96	84.04	26.68	78.54	31.83	49.86	56.54
	Min	93.80	57.70	9.90	55.10	14.18	39.50	48.19
	Max	153.00	134.00	58.49	97.40	41.38	61.90	59.54
Total Hardness (as $CaCO_3$)	Avg	549.22	337.24	38.25	345.68	36.18	379.35	28.28
	Min	494.70	262.80	28.63	251.90	19.41	288.50	12.59
	Max	606.90	421.60	56.70	398.70	58.49	444.20	52.46
Alkalinity (as $CaCO_3$)	Avg	364.46	129.74	62.94	66.78	81.05	63.52	82.20
	Min	298.00	114.00	57.16	51.20	76.71	46.80	78.92
	Max	414.60	146.30	68.49	82.50	83.37	87.40	84.75
pH*	Avg	7.80	9.49		7.37		7.23	
	Min	7.62	9.28		7.20		7.10	
	Max	8.03	9.74		7.50		7.32	
Turbidity**	Avg	21.20	26.00	-11.28	6.05	71.90	4.98	77.18
	Min	16.00	17.00	-30.77	4.50	53.89	2.20	61.11
	Max	26.00	32.00	32.00	8.30	81.54	7.00	89.52
Calcium	Avg	140.00	69.40	49.92	66.80	51.81	68.20	51.07
	Min	112.00	63.00	43.75	56.00	43.75	58.00	45.52
	Max	170.00	77.00	54.71	78.00	60.56	82.00	57.04
Magnesium	Avg	22.54	19.04	15.44	18.74	16.79	18.50	17.80
	Min	21.30	18.00	8.80	17.50	9.72	17.00	12.50
	Max	23.80	20.00	18.70	20.00	23.04	19.40	26.09

% indicates percent removal over influent

* as $-\log_{10}(H^+)$

** as JTU

TABLE A7: PILOT PLANT OPERATING DATA FOR THE WEEK OF 11/15-11/21

		Influent	Following Densator		Following Filtration		Following Activated Carbon Adsorption	
		mg/l	mg/l	% Removal	mg/l	% Removal	mg/l	% Removal
Suspended Solids	Avg	85.00	58.80	16.35	11.80	79.98	13.60	75.84
	Min	36.00	24.00	-44.62	8.00	55.56	3.00	44.44
	Max	184.00	127.00	86.96	16.00	90.00	20.00	96.25
BOD_5	Avg	68.66	12.07	80.30	11.50	81.88	11.48	81.96
	Min	52.60	11.70	77.76	11.10	78.71	11.20	78.71
	Max	84.00	12.30	84.14	11.90	85.53	11.90	84.53
PO_4	Avg	4.40	1.02	76.42	0.28	89.94	0.28	94.47
	Min	2.40	0.79	67.08	0.02	66.67	0.03	91.61
	Max	6.27	1.44	83.85	0.80	99.68	0.40	98.75
C.O.D.	Avg	173.60	153.00	8.32	104.50	38.81	72.30	57.51
	Min	125.00	120.00	-26.40	75.20	22.90	50.70	51.22
	Max	253.00	178.00	36.17	148.00	47.78	88.40	65.06
Total Hardness (as $CaCO_3$)	Avg	524.76	450.38	22.75	367.04	29.74	357.72	31.74
	Min	389.60	202.60	-19.16	239.90	6.26	235.30	-2.47
	Max	768.80	951.00	51.66	540.50	42.55	591.20	47.10
Alkalinity (as $CaCO_3$)	Avg	460.70	249.26	43.20	162.52	63.59	169.78	61.39
	Min	341.30	165.60	-1.22	55.40	28.51	49.10	23.50
	Max	609.30	345.50	65.99	289.20	88.62	270.20	89.92
pH*	Avg	7.93	9.31		7.77		7.54	
	Min	7.17	7.88		7.52		7.43	
	Max	8.42	10.43		8.48		7.65	
Turbidity**	Avg	34.20	43.80	13.30	7.24	79.00	8.88	73.79
	Min	25.00	13.00	-80.00	3.90	72.50	6.20	68.57
	Max	40.00	125.00	67.50	11.00	88.00	12.00	84.50
Calcium	Avg	119.00	80.20	34.74	77.80	35.57	78.80	35.48
	Min	103.00	38.00	1.41	57.00	18.31	49.00	9.15
	Max	142.00	140.00	64.49	116.00	52.89	129.00	54.21
Magnesium	Avg	21.02	19.04	9.90	18.52	12.25	19.28	8.65
	Min	19.90	12.70	-4.37	12.30	-3.11	12.40	-8.40
	Max	21.90	22.90	36.18	22.50	38.19	23.80	37.69

% indicates percent removal over influent

* as $-\log_{10}(H^+)$

** as JTU

TABLE A8: PILOT PLANT OPERATING DATA FOR THE WEEK OF 11/22-11/30

		Influent	Following Densator		Following Filtration		Following Activated Carbon Adsorption	
		mg/l	mg/l	% Removal	mg/l	% Removal	mg/l	% Removal
Suspended Solids	Avg	53.83	58.00	-1.37	11.00	79.07	9.17	82.53
	Min	44.00	38.00	-38.32	2.00	70.45	1.00	61.36
	Max	72.00	107.00	16.67	14.00	95.56	17.00	98.08
BOD_5	Avg	50.73	14.58	68.35	14.03	66.08	15.47	66.59
	Min	30.10	9.50	36.54	13.20	32.56	12.60	34.22
	Max	70.10	19.10	81.77	20.30	76.32	19.80	77.75
PO_4	Avg	2.65	0.27	56.81	0.08	84.23	0.14	68.91
	Min	0.33	0.01	-52.17	0.01	33.33	0.03	6.06
	Max	5.40	0.69	99.76	0.22	99.76	0.31	99.40
C.O.D.	Avg	98.38	93.83	-1.83	95.03	-2.77	69.72	17.63
	Min	28.40	51.80	-45.17	67.80	-58.11	44.90	-36.75
	Max	137.00	156.00	53.94	123.00	31.53	111.00	56.42
Total Hardness (as $CaCO_3$)	Avg	463.45	321.82	30.48	366.07	20.96	371.78	19.93
	Min	421.60	270.80	15.98	302.40	-7.32	300.00	-8.29
	Max	505.20	375.30	39.47	482.00	38.32	487.10	36.49
Alkalinity (as $CaCO_3$)	Avg	403.08	192.77	44.64	75.33	80.40	72.42	81.23
	Min	242.00	123.90	0.79	36.50	67.80	45.10	73.90
	Max	548.50	240.10	76.91	134.40	93.20	118.00	90.04
pH*	Avg	7.78	10.2		7.68		7.50	
	Min	7.32	9.19		6.80		7.13	
	Max	8.30	11.45		8.90		7.98	
Turbidity**	Avg							
	Min	No Data						
	Max							
Calcium	Avg	108.50	92.00	15.86	98.83	11.52	96.83	13.34
	Min	91.00	63.00	-32.09	68.00	-30.00	65.00	-30.53
	Max	144.00	134.00	38.74	162.00	35.14	162.00	36.94
Magnesium	Avg	20.77	16.10	23.23	15.15	26.86	15.57	24.47
	Min	17.60	8.20	-6.88	9.60	-6.45	10.60	-6.45
	Max	23.80	21.80	53.41	21.70	45.45	21.70	45.80

% indicates percent removal over influent

* as $-\log_{10}(H^+)$

** as JTU

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